U.S. Coast Guard Research and Development Center

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Full-Scale Testing of Water Mist Fire Suppression Systems in Machinery Spaces

FINAL REPORT
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16. Abstract

This report provides an evaluation of the fire fighting capabilities of the state-of-the-art water mist fire suppression systems in machinery space applications. The primary objective of this investigation was to evaluate the applicability of the International Maritime Organization's test protocol to machinery spaces with larger volumes, high ceilings and larger vent openings. In addition, the effects of compartment parameters (shape and height), mist system parameters (nozzle height and discharge rate), and fire parameters (heat release rate, fire type, and location) were also evaluated. Extinguishment times in the over 150 tests ranged from under one minute to as long as twelve minutes with some fires never extinguished. The following water mist systems were included in this evaluation: Grinnell AquaMist, Kidde Fenwal, Reliable, Securiplex, and Spraying Systems.

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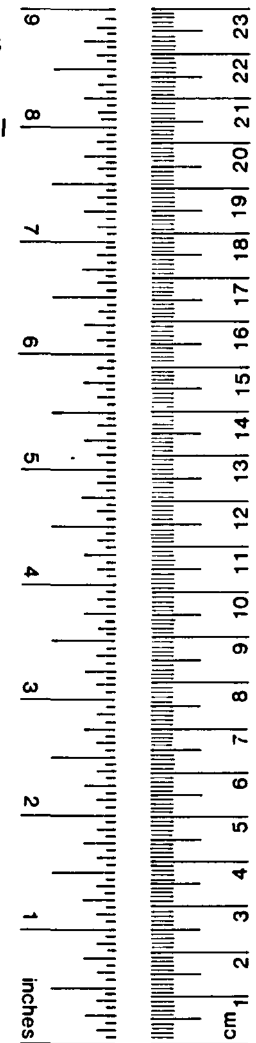
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

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cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
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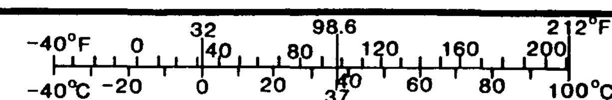

EXECUTIVE SUMMARY

The results of a series of full-scale water mist tests are reported. The Research and Development Center (RDC) evaluated several different water mist technologies to assess their effectiveness at protecting shipboard machinery spaces. RDC also evaluated portions of the recently developed International Maritime Organization's (IMO) approval guidelines for equivalent water-based fire extinguishing systems. This report addresses the abilities and limitations of these water mist technologies in protecting a shipboard machinery space. Limitations in the IMO guidelines and recommended changes are also presented.

The Montreal Protocol, an International Treaty, established production bans on Halon fire suppression agents. The ban was based on Halon's contribution to the destruction of the earth's stratospheric ozone layer. For most of the industrial world, this production ban became effective in 1994. Halon fire suppressant agents, particularly Halon 1301, had become a common fixed fire protection choice on marine vessels. With the production ban came a need to find acceptable alternatives for these applications. One of the proposed alternative technologies was fine-sized water spray, commonly called water mist.

Halon 1301 fire protection systems are installed in machinery spaces onboard many Coast Guard cutters. If existing supplies become depleted, alternative systems would need to be installed. There is a need to identify alternative systems for new cutter designs. Replacement halocarbon gaseous agents had been investigated and there was a desire to look at water mist technologies due to their environmental friendliness and lack of harmful byproducts.

In December 1994, the IMO's Maritime Safety Committee (MSC) approved guidelines for alternative arrangements for halon extinguishing systems (MSC/Circ. 668). The guidelines contain an annex that is an interim test method for fire-testing equivalent water-based fire extinguishing systems for machinery spaces and cargo pump rooms. The test method had never been tested, nor was its effectiveness for evaluating this new technology known. The Coast Guard, as part of its regulatory authority, needed to evaluate the interim test method before it could consider approvals based upon testing performed to it.

The overall objective was to evaluate the applicability of the test protocol with larger volumes, higher ceilings and larger vent openings. Over 150 full-scale fire suppression tests were conducted during this evaluation. Five water mist fire extinguishing systems were evaluated. The systems included Grinnell's AM-10 nozzles (a low pressure single fluid), a Kidde-Fenwal nozzles (low pressure single fluid), Reliable's MistaFire nozzles (high pressure single fluid), Securiplex System 2000 (low pressure twin fluids), and Navy experimental design nozzles (high pressure single fluid). The fires included a mix of spray and pan fires using either heptane or diesel fuel.

The most significant findings are:

- Water mist systems were found to require minutes to extinguish most fires as opposed to fractions of minutes for halocarbon gaseous agents. Securing ventilation and closing vent openings can potentially reduce these times.

- Water mist systems were found to dramatically reduce temperatures within the space. This can offset the disadvantages of the longer extinguishment times.

- Larger fires were easier to extinguish (with extinguishment occurring much faster) than smaller fires.

- Systems that produced small drops with high momentum demonstrated superior fire extinguishing performance during this evaluation.

- Increased mist discharge rates can increase system performance. This increase in performance is most pronounced with obstructed fires.

- The nozzles that were tested had the same effectiveness at heights 2.5 m greater than the IMO test method maximum of 5 m.

Based upon the relationship found between a fire's extinguishment and the depletion of the oxygen concentration, a model was developed to predict extinguishment time, given compartment, ventilation and mist parameters. This model can be used to identify the critical fire size (the fire size below which the system cannot extinguish the fire) for a given compartment. Fire size can then be evaluated to determine if the fire is small enough to be effectively hand fought.

Recommendations are made to change the IMO test protocol. They include requiring that systems for spaces greater than 500 m^2 be tested in a space sized to the maximum allowable for the system's design. The maximum installation height of nozzles tested to the 5 m height can be extended to 7.5 m based on the demonstrated capabilities found in these tests.

In summary, current water mist technologies were found effective at extinguishing most fires. However, extinguishment can take significantly longer than gaseous agents, but this is offset by the superior cooling and reduction of the thermal assault on the compartment boundaries. This environmental friendly fire suppression technology has the potential to effectively protect ship machinery spaces.

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1.0 INTRODUCTION

The United States Coast Guard has been actively involved in the research effort to identify alternative fire suppression methods and/or agents for Halon 1301 total flooding systems. Specifically, the Safety & Human Resource Division (SHRD) of the Coast Guard's Research and Development Center has been conducting research in this area. The research, to date, has focussed primarily on the gaseous halon alternatives. Recent developments in the International Maritime Organization (IMO) are allowing water mist technologies to be installed in machinery space applications as well as other areas in foreign-flagged ships. These recent developments are of interest to the Coast Guard for two reasons: (1) to provide protection of the machinery spaces for their new class of cutters (G-SEN), and (2) to provide data for U.S. regulatory acceptance of water mist technologies (G-MSE). Consequently, this project has two Coast Guard Headquarters sponsors; the Marine Safety and Environmental Protection Organization (G-MSE) and the Systems Organization (G-SEN).

In December 1994, the IMO Maritime Safety Committee approved guidelines for alternative arrangements for halon fire extinguishing systems (MSC Circular 668) [1]. Annex B of the guidelines provides an interim test method for evaluating equivalent water-based fire extinguishing systems for Category A machinery spaces and cargo pump rooms. Since the development of the guidelines, testing conducted for U.S. Army Watercraft [2] and U.S. Navy ships [3] has demonstrated that, if properly designed and tested, water mist fire suppression systems can afford effective protection of Category A machinery spaces. These tests have also identified areas in the standard that need to be clarified as well as other concerns such as areas in need of separate dedicated protection schemes (i.e., bilges).

The tests conducted to date form a substantial database for water mist systems installed in the overhead of machinery spaces having volumes between 250-750 m^3 and ceiling heights up to 6 m. These spaces are significantly smaller than "typical" shipboard machinery spaces. Unfortunately, it is uncertain how to extrapolate these data to spaces with larger volumes and/or spaces with greater ceiling heights. The current IMO test protocol for machinery spaces makes a distinction between spaces less than and greater than 500 m^3. For spaces less than 500 m^3, the test protocol consists of evaluating the candidate water mist system in a 10 m x 10 m x 5 m enclosure against 13 fire scenarios of various sizes and types. Unfortunately, there appears to be insufficient data to support the applicability of these results to spaces with similar volumes but varying shapes and heights. For spaces greater than 500 m^3, the systems are evaluated in a large burn building in the absence of an enclosure against the 13 previously mentioned fire scenarios. The open space tests are applicable to extremely large machinery spaces but are unrealistically severe for intermediate size machinery spaces (500 m^3 - 3000 m^3). This experimental program along with research to be conducted at Factory Mutual were initiated to address many of these unresolved issues pertaining to the use of water mist in "typical" machinery space applications.

2.0 OBJECTIVES

The overall objective of this test series was to evaluate the applicability of the IMO test protocol to machinery spaces with larger volumes, high ceilings and larger vent openings. As testing proceeded, it became possible to address the following more specific objectives:

- Evaluate the effects of the compartment parameters (size, shape and height) on the fire extinguishing capabilities of the current water mist technologies.

- Evaluate the effect of ceiling/nozzle height on the system capabilities.

- Evaluate and compare the capabilities of a group of representative water mist technologies.

- Evaluate the ease of extinguishment of a fire as a function of size, type and location.

- Evaluate the effect of increased mist discharge rate (approximately double) on the fire extinguishment capabilities of a candidate water mist system.

- Evaluate the effect that open roof vents have on the fire extinguishment capabilities of the candidate water mist systems. The intention was to minimize the effects of oxygen depletion producing conditions more representative of larger machinery spaces).

3.0 TECHNICAL APPROACH

The tests conducted for U.S. Army Watercraft focussed on the interim test method for machinery spaces both smaller and larger than 500 m^3. The data provides a limited basis for extrapolating the results from a 500 m^3 space to larger spaces assuming the ceiling height and ventilation conditions of the space are not increased (extrapolation in the horizontal direction). This was demonstrated during tests conducted in spaces 9.1 m x 9.1 m x 4.5 m and 18.2 m x 9.1 m x 4.5 m which showed only marginal variations in fire suppression characteristics between the two enclosures. Additional data is required to bound the limits of this horizontal extrapolation. Further questions still remain regarding the extrapolation of the data to much larger spaces with greater ceiling heights and larger vent openings.

This test series was designed to serve as an extension of the U.S. Army Watercraft test program. During the initial stages of this investigation, two water mist systems were evaluated. The first system was a high-pressure, single-fluid system, produced using industrial spray nozzles (Spraying Systems' Model 7N). This system passed the IMO test protocol during the U.S. Army Watercraft tests, and exhibited superior performance in the Navy test program. The second system was a commercially available, low-pressure, single-fluid system (Grinnell AquaMist AM-10). This system was also evaluated in both test series and produced mixed results. The rationale behind selecting two different types of water mist systems was to determine not only if the results from both technologies could be extrapolated in all three dimensions, but also to determine if this extrapolation affects one type of technology greater than another.

Three additional systems/technologies were also included to provide additional data on systems that use different mechanisms for generating mist. These systems include systems produced by Kidde Fenwal, Reliable and Securiplex. These systems are further described in Section 4.3.3 of this report.

The test program began with an evaluation of the effects that the compartment geometry (size, aspect ratio, and height) has on the overall performance of the system(s). This was accomplished by first comparing the data from the initial phase of this program to the U.S. Army Watercraft and U.S. Navy data. These three programs were conducted in spaces of similar size (volumes), but with dramatically different shapes (aspect ratios). The second set of tests were designed to identify any variations in fire suppression capabilities as a function of vertical distances between the fire and the mist nozzle(s). This was accomplished by re-evaluating the two primary systems against the fires in the IMO test protocol with the nozzles installed higher in the space (7 m versus 5 m). The final phases of this investigation was intended to address the use of water mist in larger machinery spaces.

The initial assessment of vertical extrapolation was the evaluation of the two primary systems against the IMO test protocol in a machinery space containing either a large vent opening in the overhead or with no overhead at all. This, in theory, produced a worst-case scenario where oxygen depletion could only occur on a localized scale, the temperatures in the space remained low, and the loss rate of mist out of the vent opening was significantly high. This scenario is representative of a machinery space with a ceiling height much greater than five meters. It is perceived that such a space would be protected with arrays of nozzles stacked vertically with a 5.0 m separation. The lack of mist contribution from nozzles which would typically be installed higher in the space also exaggerates the severity of the scenario.

Additional tests were also conducted to evaluate the ease or difficulty of extinguishing various sizes and types of fires (spray and pan). The effects of fire location were also evaluated. The final phase of the program looked at the effect of increasing the mist discharge rate on the fire extinguishing capabilities of the water mist system consisting of high-pressure industrial spray nozzles. This evaluation was conducted with the standard IMO vent and the open roof vent configuration.

4.0 TEST PARAMETERS

4.1 Machinery Space Configuration

The tests were conducted at the U.S. Coast Guard Fire and Safety Test Detachment on the test vessel, MAYO LYKES, located at Little Sand Island in Mobile, AL. The #4 cargo hold was modified to simulate a "typical" machinery space (Figures 1 and 2). This modification was accomplished during the gaseous halon alternatives program [5]. The space is roughly 6.9 x 11.1 x 7.3 m (560 m^3) and is bounded by metal bulkheads. Two levels of catwalks have been installed in the space as shown in Figure 2. These catwalks allow easy access to critical areas in the space and, to some degree, serve as obstructions for the water mist systems. The catwalks located high in the space were constructed with metal grating and the lower catwalks were constructed of steel plating. A 2 m x 2 m vent was added in the aft bulkhead on the second deck level to comply with the IMO interim water mist test protocol [1]. During the open roof vent tests, 25% of the overhead of the space was removed. The diesel engine mock-up situated in roughly the center of the compartment was modified to replicate the mock-up specified in the IMO test protocol. The modified mock-up is shown in Figure 3.

4.2 Ventilation System

The ventilation system installed for the gaseous halon alternative program [5] was used during the preburn to maintain the oxygen concentration in the space and after each test to clear the space of mist and products of combustion (Figure 4). This ventilation system provides approximately 15 air changes per hour, an average value used in USCG Cutter machinery spaces [5]. The ventilation system consists of a Dayton model 7H170 blower to supply air at a rate of 170 m^3/min into the space. The supply entered the space through the aft bulkhead at a height 1.2 m above the lower deck, then branched vertically to provide inlet air both high and low in the space. The exhaust air exited the space through the IMO standard vent opening.

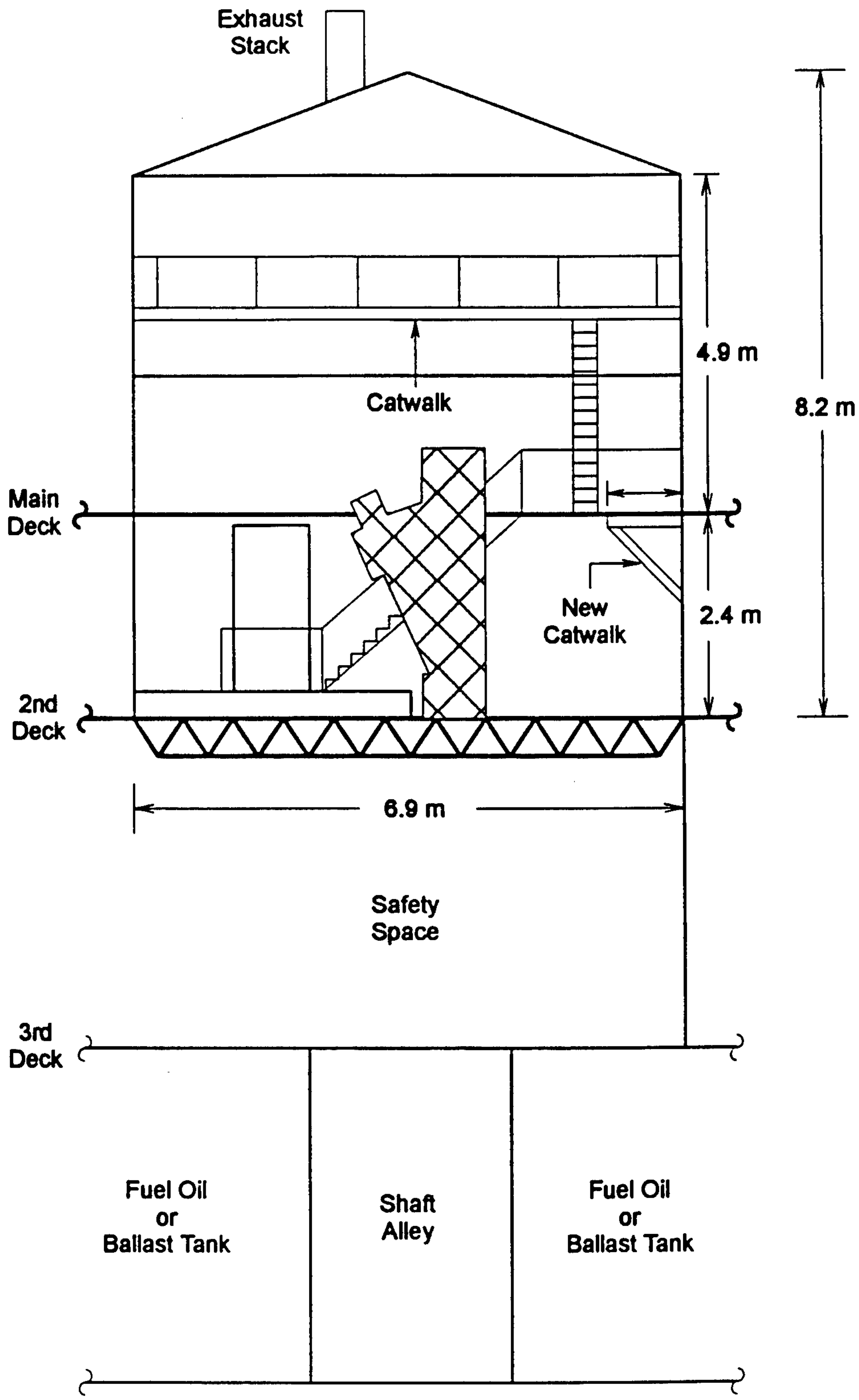


Figure 1. Machinery Space Mock-up Elevation

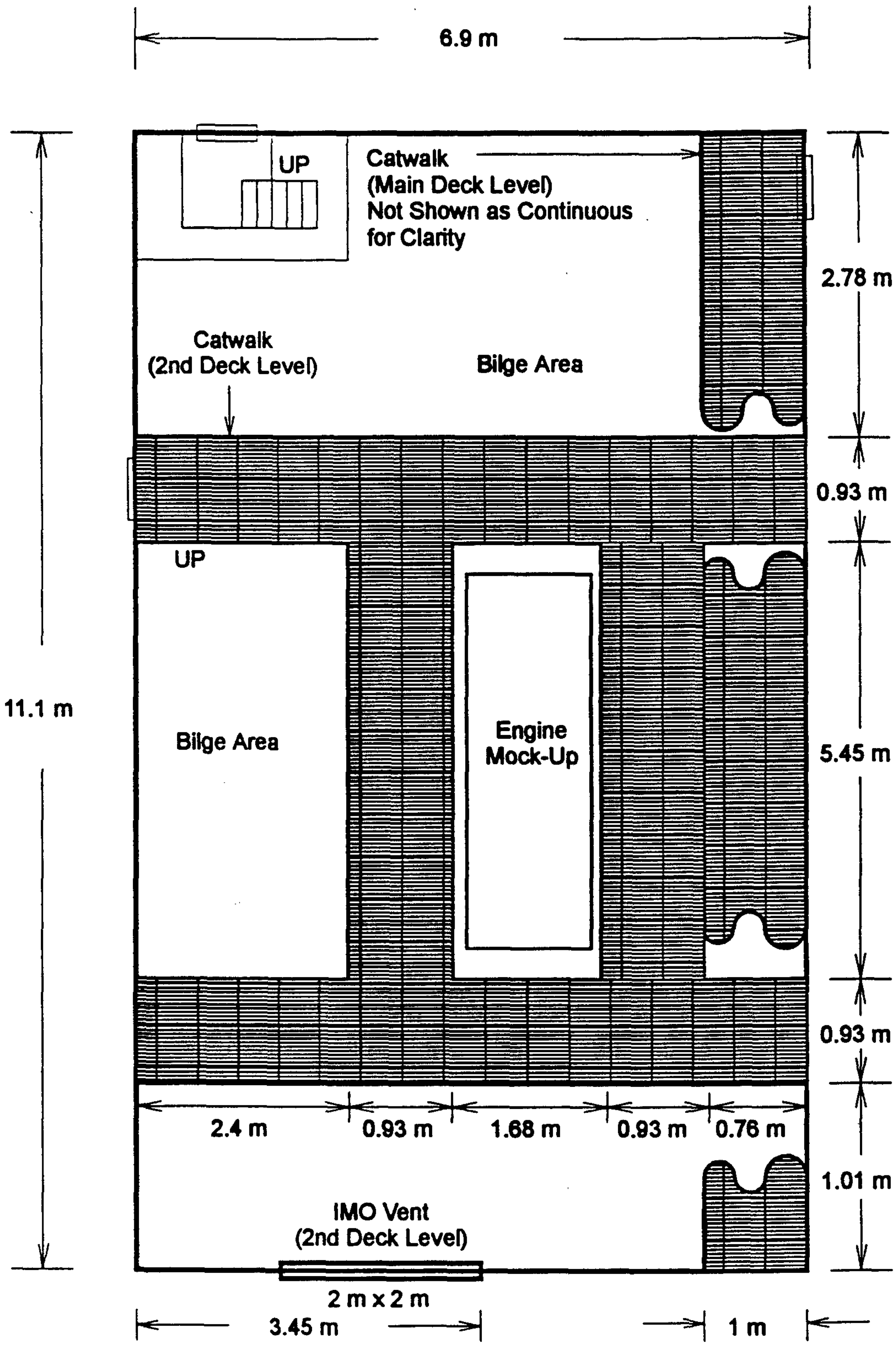
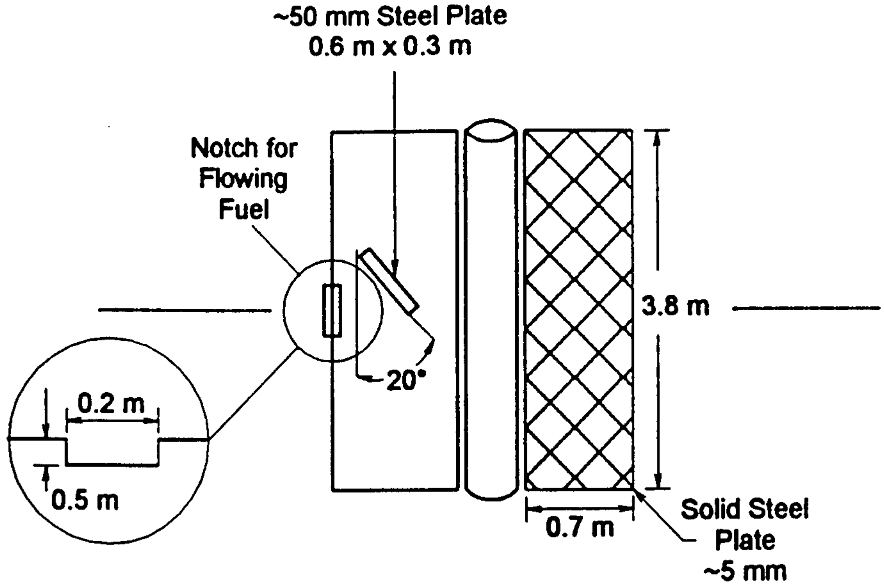


Figure 2. Machinery Space Mock-up Plan View



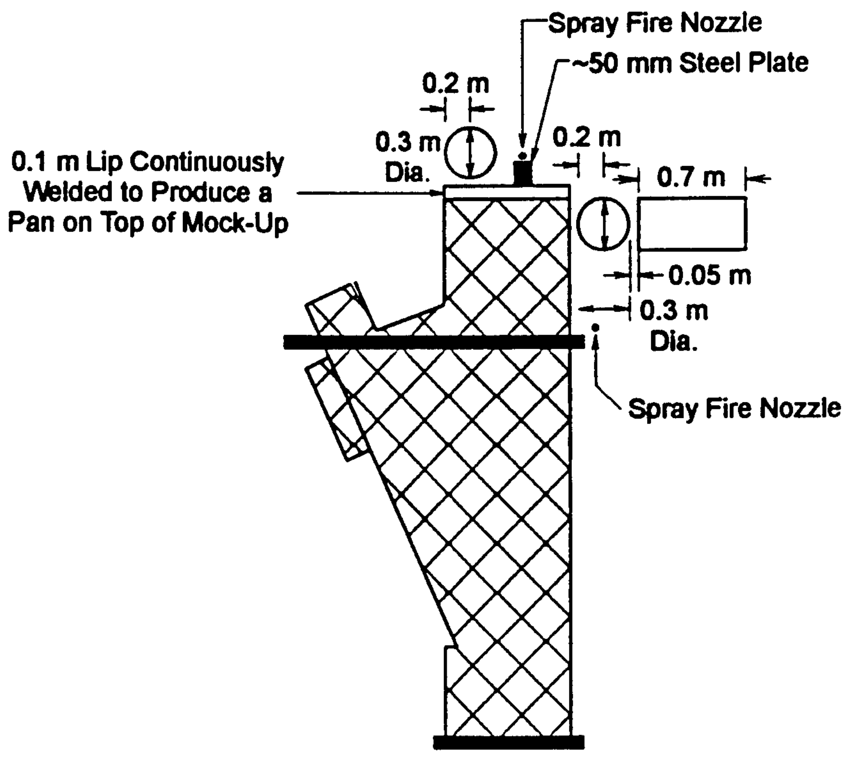


Figure 3. Modified Engine Mock-up

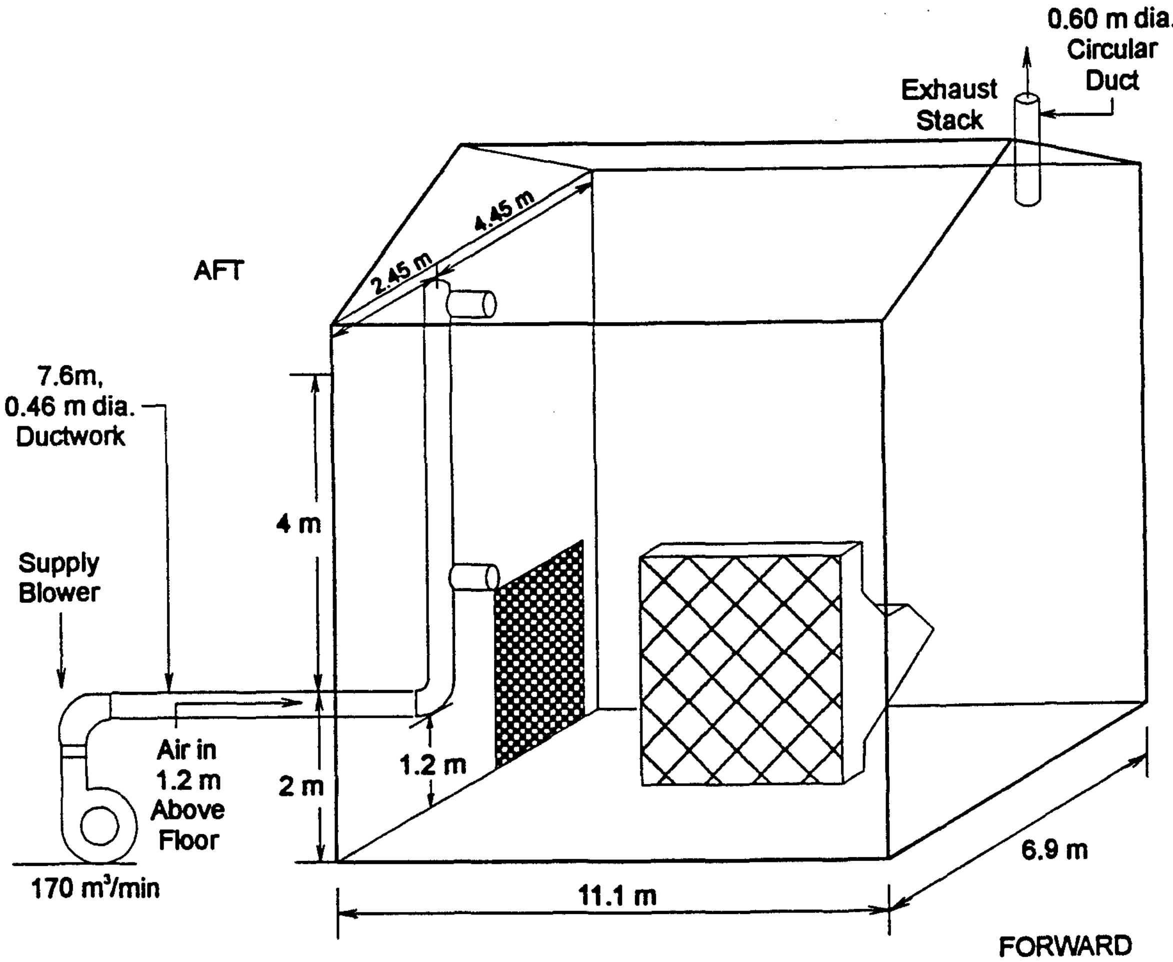


Figure 4. Ventilation System

Also, fans located in the hull of the ship, both forward and aft, were operating during these tests. The fans were used to keep the area surrounding the test compartment clear of smoke and mist.

4.3 Water Mist Extinguishing System

4.3.1 Pumping System

The high-pressure water mist systems evaluated during this test series were supplied using the pumping system shown in Figure 5. The pumping system consisted of ten gasoline combustion engine-driven, high-pressure washers each capable of delivering a total flow rate of 27 Lpm (7 gpm) at a pressure of 200 bar (3000 psi). These pumps were supplied with fresh water using a submersible pump located on a storage barge adjacent to the MAYO LYKES. The low-pressure systems were supplied using the ship's fire pump, which has a capacity of 570 Lpm (150 gpm) at a pressure of 17.5 bar (250 psi).

4.3.2 Piping Network

The piping network shown in Figure 6 was installed at both the 5.0 m and 7.0 m elevation. The system was constructed of 2.5 cm (1 in.) stainless steel tubing, with a 2.1 mm (0.083 in.) wall thickness) and connected together using stainless steel compression fittings. Stainless steel tubing and fittings were required to prevent rust and/or corrosion from developing inside the piping network. This system design has a working pressure of 200 bar (3000 psi) and a burst pressure of 800 bar (12,000 psi). Each nozzle grid contained 28 nozzles installed 1.5 m (5 ft) on center. This spacing relates to an individual nozzle coverage area of 2.3 m^2 (25 ft^2). The flow rate of the nozzles ranged from 5.0 to 11.4 Lpm (1.3 to 3.0 gpm), producing a water application rate (total flow/protected area) of 2.2 to 5.0 Lpm/m^2 (0.05 to 0.12 gpm/ft^2).

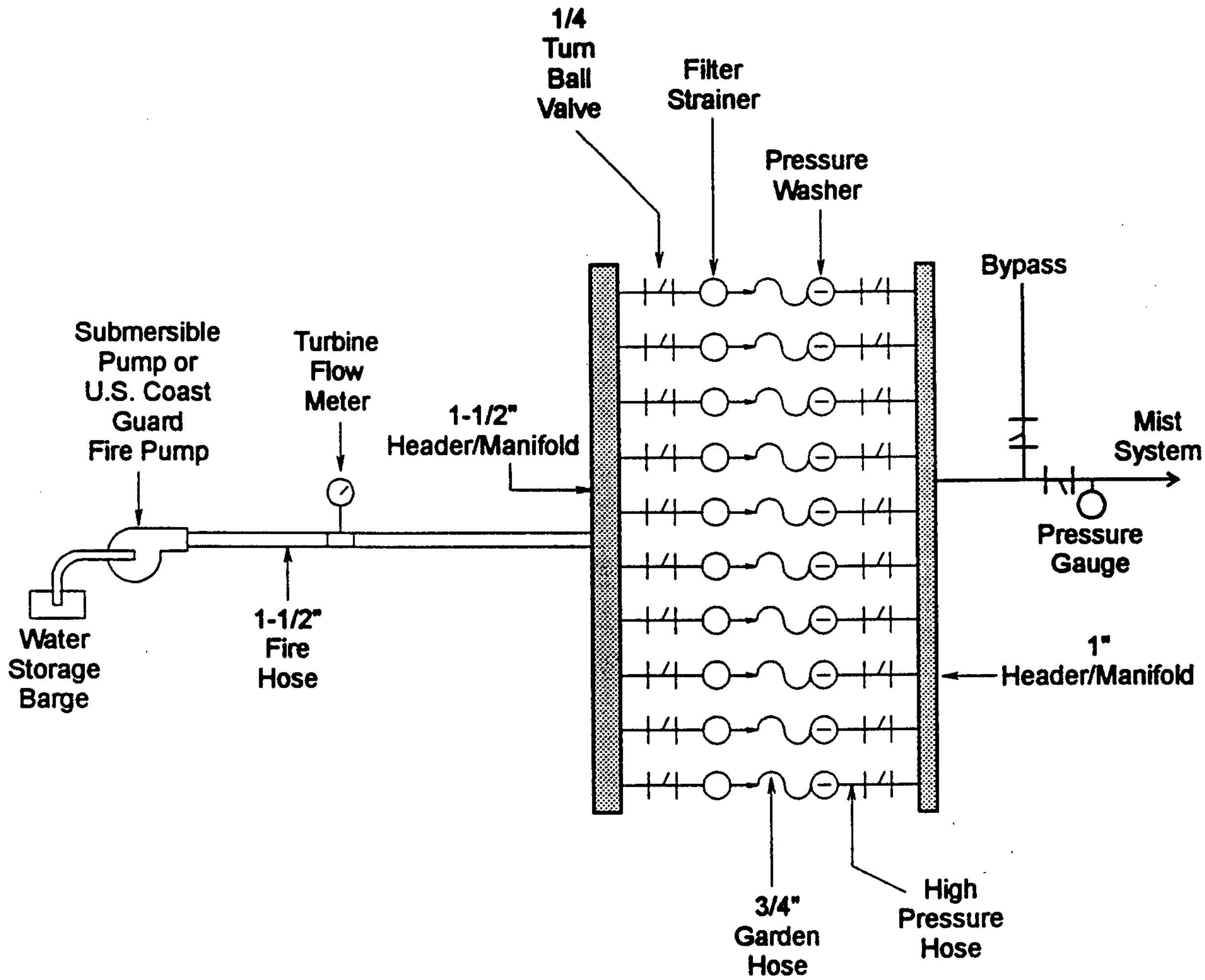


Figure 5. Water Mist Pumping System

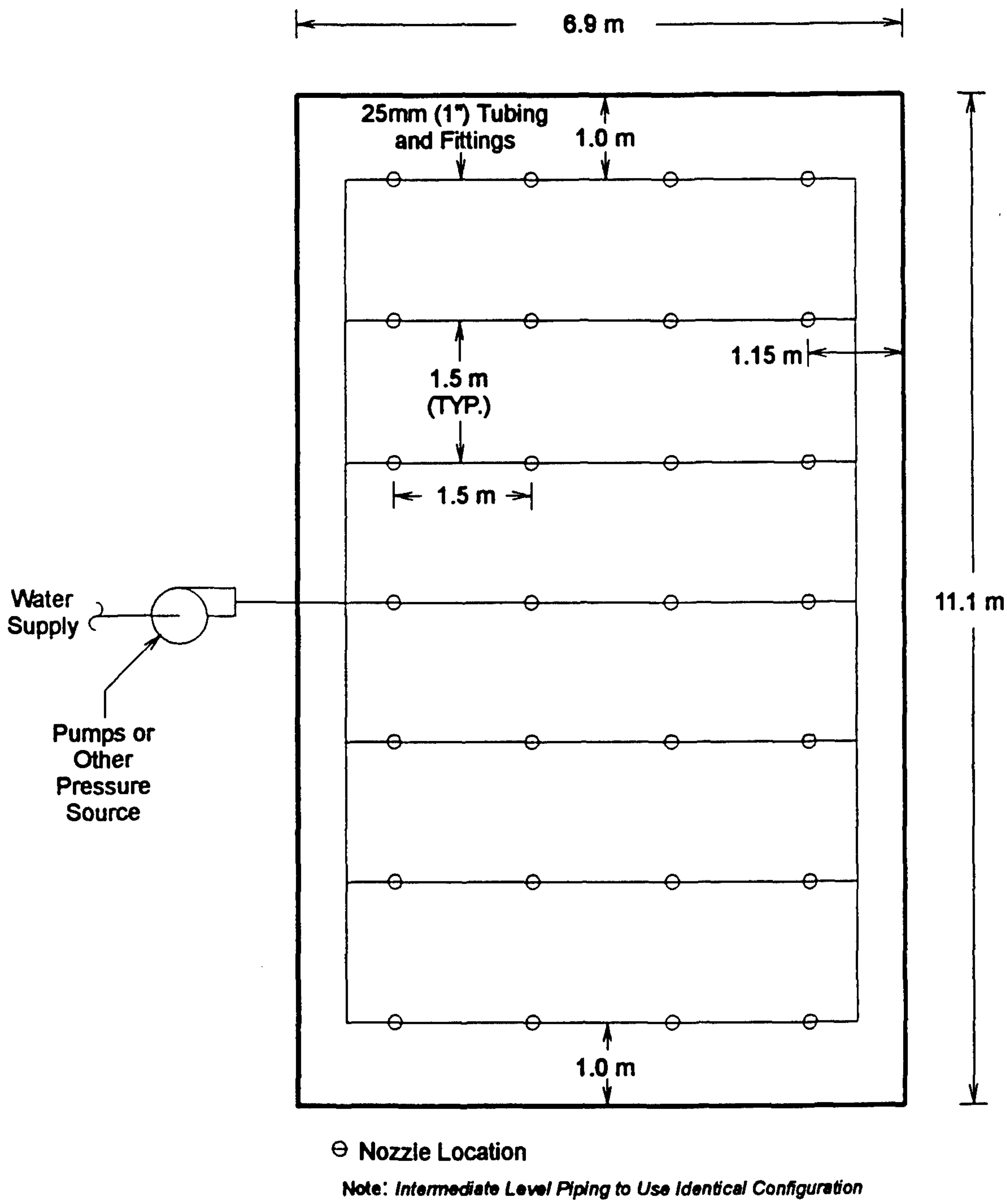


Figure 6. Water Mist Piping and Nozzle Locations

4.3.3 Candidate Systems/Nozzles

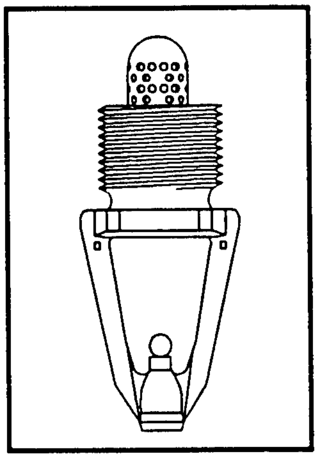
Five water mist fire extinguishing systems were evaluated during this test series (Grinnell AquaMist, Kidde Fenwal, Reliable, Securiplex and Spraying Systems). The candidate nozzles cover the range of available technologies from high and low-pressure single-fluid systems to twin-fluid systems. The individual nozzles are designed to flow 5.0 to 11.4 Lpm (1.3 to 3.0 gpm) and operate at pressures ranging from 5.5 to 70 bar (80-1000 psi). The candidate systems/nozzles are shown in Figure 7. A brief description of each nozzles type is listed as follows:

4.3.3.1 *Grinnell AquaMist Nozzle (AM-10)*

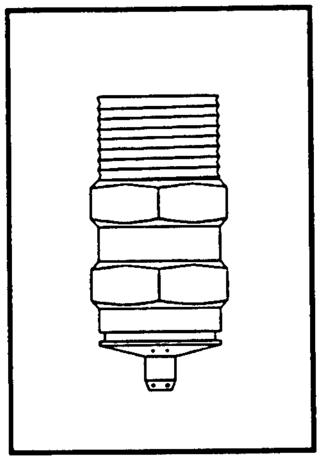
Grinnell AquaMist (AM-10) nozzle is a single-fluid, low-pressure nozzle which has a working pressure of 12 bar (175 psi) and is similar to a standard automatic sprinkler system in terms of system hardware and operating principles. It produces small droplets by impinging a water stream on a spherical deflector plate. The relatively low-pressure AquaMist nozzle produces larger droplets than the other technologies ($Dv_{50} \approx 500$ microns). The system has the advantage of being less expensive than the high-pressure systems and can incorporate a majority of the hardware used by conventional sprinkler systems. The nozzle used for this evaluation (AM-10) has a nominal k-factor of 3.5 Lpm/bar^{½} (0.26 gpm/psi^{½}) and is typically installed with a 2.0 m (6.6 ft) nozzle spacing. During these tests, the nozzles were installed with a 1.5 m (5.0 ft) nozzle spacing resulting in a nominal mist application rate (flow rate per unit area) of 5.0 Lpm/m^2 (0.12 gpm/ft^2).

4.3.3.2 *Kidde-Fenwal Nozzle*

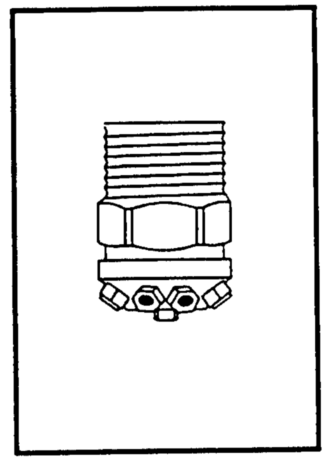
The Kidde-Fenwal mist nozzle is a low-pressure, single-fluid nozzle which has a working pressure of 12 bar (175 psi). It produces small droplets by impinging water streams upon one another ($Dv_{50} \approx 250 - 300$ microns). As with the Grinnell AquaMist nozzle, the low operating pressure sacrifices efficiency in producing small droplets for lower cost and the commercial advantages of using standard sprinkler-type hardware. The Kidde-Fenwal nozzle has a nominal k-factor of 3.4 Lpm/bar^{½} (0.23 gpm/psi$^{½)}$ and is typically installed with a 2.0 m (6.6 ft) nozzle



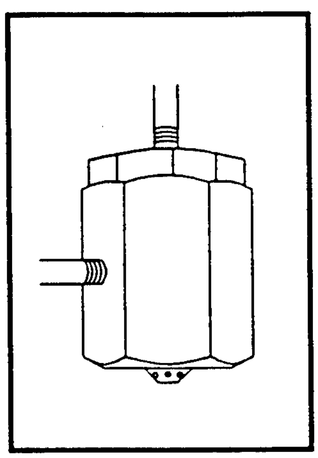
Grinnell
Aquamist
AM-10



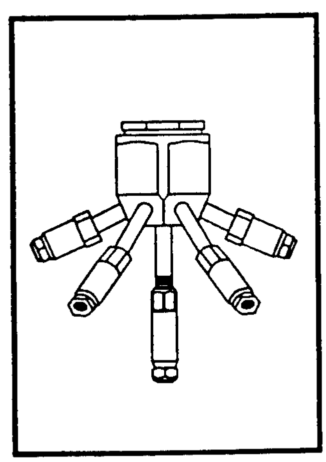
Kidde Fenwal
Mist Nozzle



Reliable
Mistafire



Securiplex
(BP Technology)



Modified
Cluster Head
Spraying
Systems

Figure 7. Candidate Water Mist Nozzles

spacing. During these tests, the nozzles were installed with a 1.5 m (5.0 ft) nozzle spacing resulting in a nominal mist application rate of 4.8 Lpm/m^2 (0.11 gpm/ft^2).

4.3.3.3 *Reliable MistaFire Nozzle*

The Reliable MistaFire system is a single-fluid, high-pressure system which has a working pressure of 70 bar (1000 psi). These nozzles produce small droplets ($Dv_{50} \approx$ 100 microns) with high momentum. The Reliable MistaFire nozzle consists of nine smaller nozzles or orifices installed in a machined brass body. The nozzle was configured with eight smaller nozzles (MX-20NP) (0.5 mm (0.02 in.) diameter orifice) installed in a circular pattern around the perimeter of the composite nozzle and one higher-flow nozzle (MX-30) (0.75 mm (0.03 in.) diameter orifice) installed in the center. In this configuration, the nozzle has a k-factor if 0.9 Lpm/bar$^{1/2}$ (0.07 gpm/psi$^{1/2}$) and was designed to be installed with a 1.5 m (5.0 ft) nozzle spacing. This nozzle spacing produces to a nominal mist application rate of 3.9 Lpm/m^2 (0.09 gpm/ft^2).

4.3.3.4 *Securiplex System 2000*

The Securiplex System 2000 is a low-pressure, twin-fluid system. Twin-fluid nozzles incorporate a secondary or atomizing fluid (air) to shear the water into small droplets. This shearing of the water into small droplets occurs inside the nozzle. The nozzle operates at 5.5 bar (80 psi) for both fluids and produces medium-size droplets (a $Dv_{50} \approx$ 200 microns) with moderate momentum. The nozzle has a recommended nozzle spacing of 1.5 m (5.0 ft). This corresponds to a nominal application rate of 2.2 Lpm/m^2 (0.054 gpm/ft^2).

During the evaluation of the Securiplex system, the 5.0 m pipe network was repositioned at an elevation of 6.5 m. The nozzles were installed in the 6.5 m network which was used to supply the nozzles with the atomizing fluid (air). One 10.0 m^3/min (350 cfm) Ingersol-Rand air compressor was used to supply air to the system. Water was provided to the nozzles via the 7.0 m pipe network using 1.0 cm (0.5 in.) flexible copper tubing.

4.3.3.5 *Modified Spraying Systems' Nozzle*

The modified Spraying Systems' nozzle was the nozzle developed for the U.S. Navy and was selected for this evaluation due to its superior fire suppression capabilities as identified during previous investigations [2,3]. The resulting system is a single-fluid, high-pressure system which was evaluated at a pressure of 70 bar (1000 psi). These nozzles produce small droplets ($Dv_{50} \approx 100$ microns) with high momentum. The nozzle consists of a Spraying Systems' Model 7N nozzle body with seven model 1/4LN nozzles installed on 7.6 cm (3 in.) long brass nipples. The six 1/4LN nozzles installed around the perimeter are Model 1/4LN2, and the one in the center is a Model 1/4LN8. The purpose of varying the sizes of these nozzles was to produce droplets of different size and momentum: the perimeter nozzles produce small droplets with low momentum, and the center nozzles produce larger droplets with higher momentum which serves to distribute the mist throughout the space. In this configuration, the nozzle has a k-factor of 0.75 $Lpm/bar^{1/2}$ (0.05 $gpm/psi^{1/2}$). These nozzles were installed with a 1.5 m (5.0 ft) nozzle spacing which corresponds to a nominal mist application rate of 2.7 Lpm/m^2 (0.07 gpm/ft^2).

During the tests conducted at Factory Mutual [7] and during many of the tests conducted later in this test series, the nozzle configuration was slightly changed. The change consisted of replacing the LN-series nozzles with T-series nozzles with the same orifice size designation. The T-series nozzles were also produced by Spraying Systems. It is believed that this substitution had little if any effect on the flow and drop size characteristics of the nozzle. These nozzles are referred to later in the text as the modified Spraying Systems' nozzle (T series orifices).

4.4 Fire Scenarios

4.4.1 IMO Fire Scenarios

The IMO FP39 Draft Standard for Machinery Spacing Testing [1] was selected as the basis for this evaluation. A copy of this draft standard is found in Appendix A. The machinery space layout and engine mock-up are shown in Figures 8 and 9. The tests required by this standard are listed in Table 1. Previous studies [2] have identified six specific IMO tests that appear to distinguish between the higher and somewhat lower performance water mist systems.

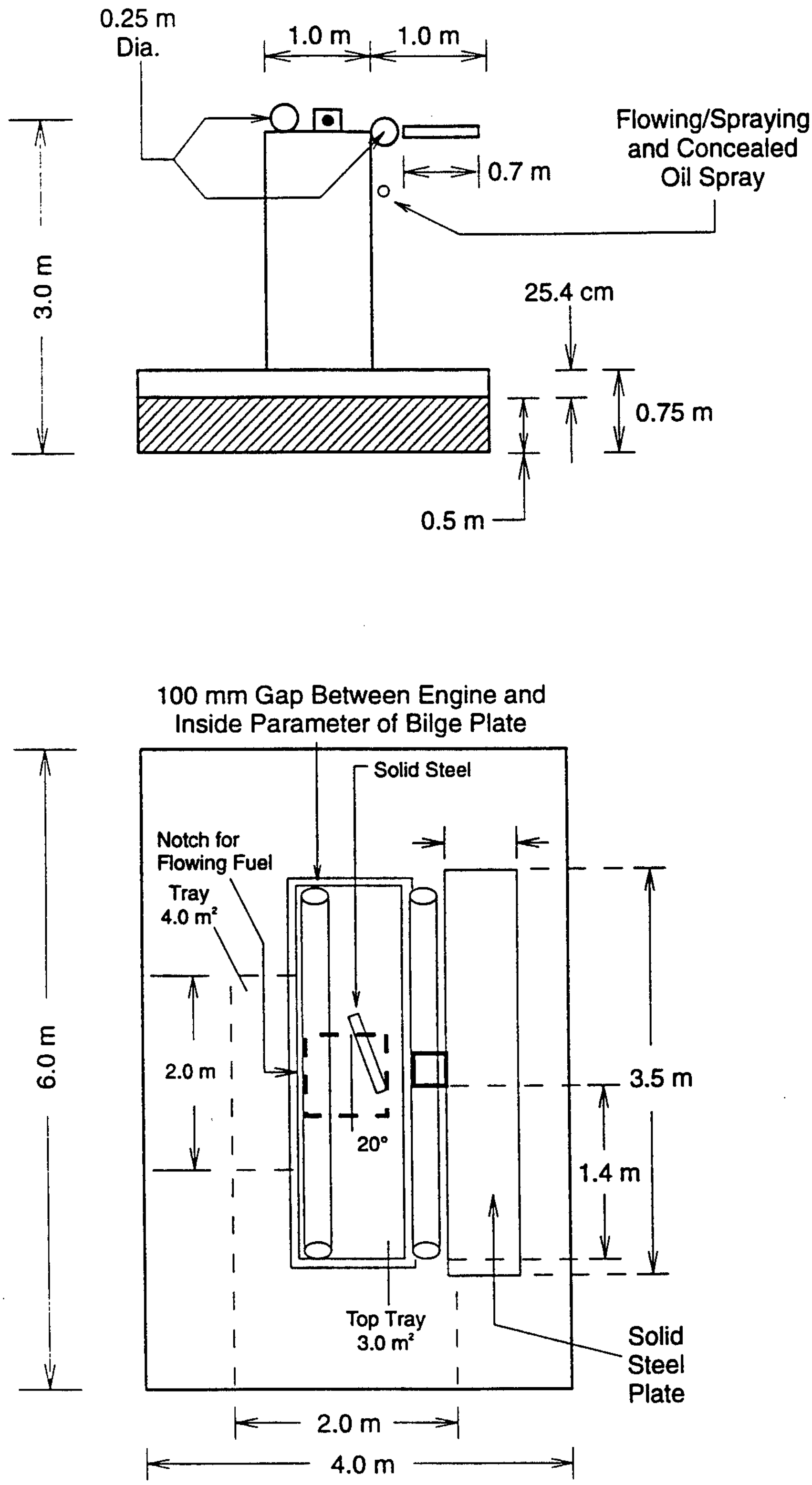


Figure 8. IMO Engine Mock-up (Front and Elevation Views)

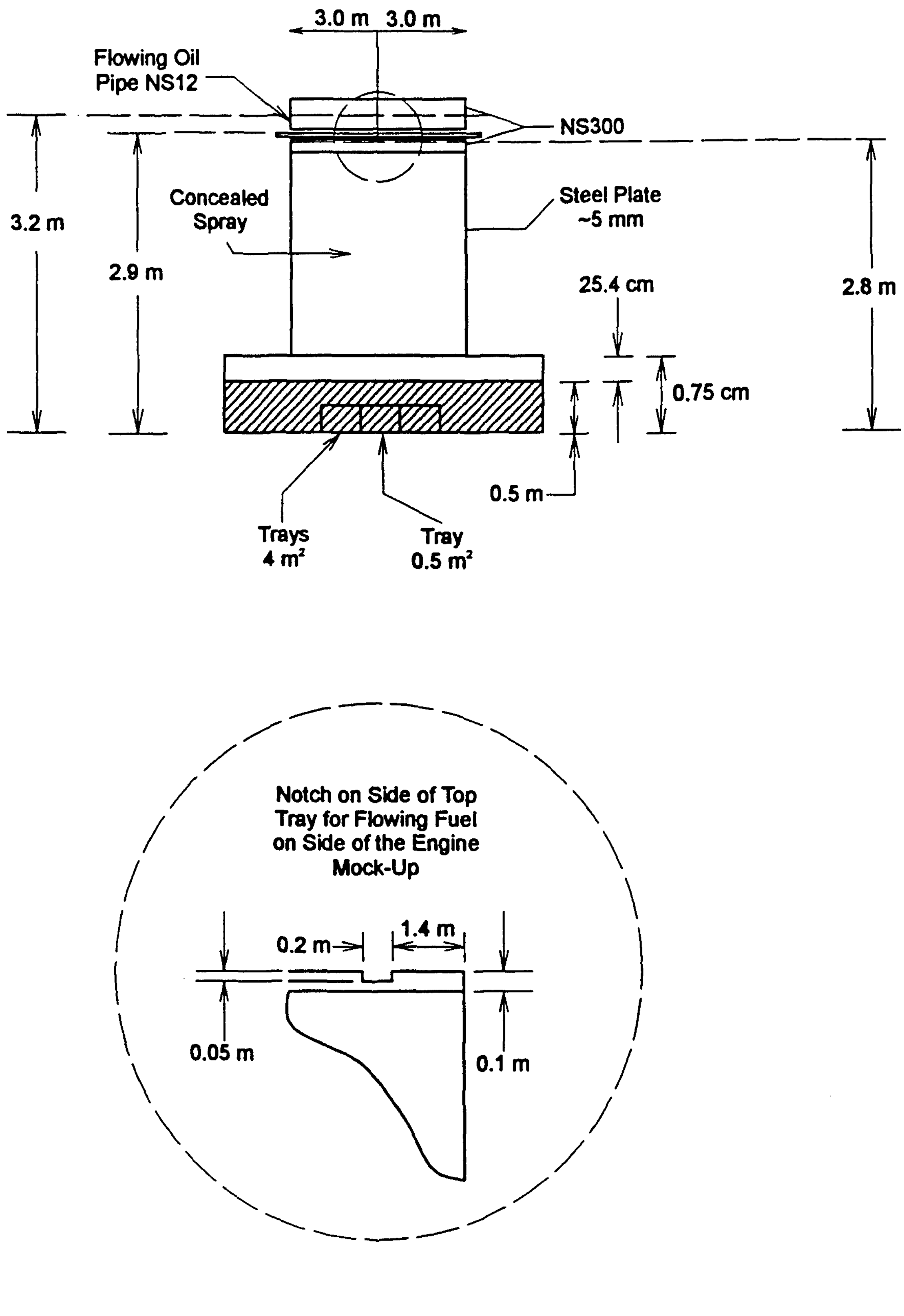


Figure 9. IMO Engine Mock-up (Side View)

These tests have been highlighted in Table 1. The tests consist of the two larger spray fires, IMO-2 and IMO-3; the two smaller spray fires, IMO-5 and IMO-6; the small pan fire, IMO-9; and the large pan fire flowing/cascading fuel fire combination, IMO-10. Specifics on the locations of each fire and how the fires are produced are found in Appendix A.

Table 1. IMO Test Protocol

Test Number	Fire Scenario	Test Fuel
IMO-1	Low-pressure spray on top of simulated engine between agent nozzles (6.0 MW)	Commercial fuel oil or light diesel fuel
IMO-2	**Low-pressure spray on top of simulated engine with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1 m away (6.0 MW)**	**Commercial fuel oil or light diesel oil**
IMO-3	**Low-pressure, concealed horizontal spray fire on side of simulated engine with oil spray nozzle positioned 0.1 m in front of the engine (6.0 MW)**	**Commercial fuel oil or light diesel oil**
IMO-4	Combination of worst spray fire from Tests 1-3 and fires in trays (4 m^2) under and on top of the simulated engine (3 m^2)	Commercial fuel oil or light diesel oil
IMO-5	**High-pressure horizontal spray fire on top of simulated engine (2.0 MW)**	**Commercial fuel oil or light diesel oil**
IMO-6	**Low-pressure low flow concealed horizontal spray fire on the side of simulated engine (1.0 MW)**	**Commercial fuel oil or light diesel oil**
IMO-7	0.5 m^2 central under mock-up	Heptane
IMO-8	0.5 m^2 central under mock-up	SAE 10W30 mineral-based lubrication oil
IMO-9	**0.1 m^2 on top of bilge plate centered under exhaust plate**	**Heptane**
IMO-10	**Flowing fuel fire 0.25 kg/s from top of mock-up (see Figures 8 and 9)**	**Heptane**
IMO-11	Class A fires UL 1626 wood crib in 2 m^2 pool fire with 30-second pre-burn	Heptane
IMO-12	A steel plate (30 cm x 60 cm x 5 cm) offset 20° to the spray is heated to 350°C by the top low-pressure, low-flow spray. Then the plate system shutoff, no reignition of the spray is permitted.	Heptane
IMO-13	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil

Note: Highlighted tests were found [2] to distinguish between higher and somewhat lower performance water mist systems.

4.4.2 ARMY Fire Scenarios

Additional fire scenarios developed during the U.S. Army Watercraft investigation [2] also provided valuable information about the systems' fire suppression capabilities. For the most part, these tests are modifications of a limited number of IMO fire scenarios with the only modification being the substitution of a lower flashpoint fuel, heptane, for the higher flashpoint diesel or commercial fuel oil. The use of heptane not only makes the fire more difficult to extinguish due to the lower flashpoint but also allows visual observation of the test due to lower smoke production. These tests were conducted using the IMO test configuration and are listed in Table 2. The tests include two large heptane spray fires, two small heptane spray fires, and a large heptane pool fire. These five fire tests along with the previously-mentioned six IMO tests served as the primary fire tests for this evaluation.

Table 2. ARMY Test Protocol

Test Number	Fire Scenario	Test Fuel
ARMY-1	Low-pressure spray fire on top of simulated engine between agent nozzles (6.0 MW)	Heptane
ARMY-2	Low-pressure low-flow spray fire on top of simulated engine between agent nozzles (1.0 MW)	Heptane
ARMY-3	3 m^2 pan fire on top of simulated engine	Heptane
ARMY-4	Low-pressure low-flow spray fire on side of simulated engine (1.0 MW)	Heptane
ARMY-5	Low-pressure spray fire on side of simulated engine (6.0 MW)	Heptane

4.4.3 USCG Fire Scenarios

In the latter stages of the program, a series of tests were conducted to evaluate the effect of fire size and location on the ease or difficulty of extinguishment. These tests consisted of five spray fire sizes and three pan fire sizes as shown in Table 3. During the spray fire analysis, five heptane spray fires were evaluated (6.0, 2.0, 1.0, 0.8 and 0.6 MW). The fires were conducted at two locations: on top of the mock-ups as described in IMO-1 and on the side of the mock-up as described in IMO-3. During the pan fire analysis, three heptane pan fires (1.0 m^2, 0.5 m^2 and 0.1 m^2) were evaluated. The sides of the pan were constructed in accordance with IMO-9. The pans were evaluated in three locations: on top of the mock-up high in the space, low in the space on the second deck, and under the mock-up obstruction plate. The fires conducted high in the space were positioned inside the 3.0 m^2 pan on top of the mock-up as described in IMO-10. The fires conducted low in the space were positioned between four nozzles and located on the second deck. The fires conducted under the obstruction plate were located on the catwalk and positioned in accordance with IMO-9.

Table 3. Coast Guard Test Protocol

Test Number	Fire Scenario	Test Fuel
USCG-1	Low-pressure spray on top of simulated engine between agent nozzles (6.0 MW)	Heptane
USCG-2	Low-pressure spray on top of simulated engine between agent nozzles (2.0 MW)	Heptane
USCG-3	Low-pressure spray on top of simulated engine between agent nozzles (1.0 MW)	Heptane
USCG-4	Low-pressure spray on top of simulated engine between agent nozzles (0.8 MW)	Heptane
USCG-5	Low-pressure spray on top of simulated engine between agent nozzles (0.6 MW)	Heptane
USCG-6	Low-pressure, concealed horizontal spray fire on side of simulated engine with spray nozzle positioned 0.1 m in front of the engine (6.0 MW)	Heptane
USCG-7	Low-pressure, concealed horizontal spray fire on side of simulated engine with spray nozzle positioned 0.1 m in front of the engine (2.0 MW)	Heptane
USCG-8	Low-pressure, concealed horizontal spray fire on side of simulated engine with spray nozzle positioned 0.1 m in front of the engine (1.0 MW)	Heptane
USCG-9	Low-pressure, concealed horizontal spray fire on side of simulated engine with spray nozzle positioned 0.1 m in front of the engine (0.8 MW)	Heptane
USCG-10	Low-pressure, concealed horizontal spray fire on side of simulated engine with spray nozzle positioned 0.1 m in front of the engine (0.6 MW)	Heptane
USCG-11	Pan fire on top of simulated engine between agent nozzles (1.0 m^2~ 3.3 MW)	Heptane
USCG-12	Pan fire on top of simulated engine between agent nozzles (0.5 m^2~ 1.6 MW)	Heptane
USCG-13	Pan fire on top of simulated engine between agent nozzles (0.1 m^2~ 250 kW)	Heptane
USCG-14	Pan fire on second deck between agent nozzles (1.0 m^2~ 3.3 MW)	Heptane
USCG-15	Pan fire on second deck between agent nozzles (0.5 m^2 ~ 1.6 MW)	Heptane
USCG-16	Pan fire on second deck between agent nozzles (0.1 m^2 ~ 250 kW)	Heptane
USCG-17	Pan fire on side of simulated engine (1.0 m^2 ~ 3.3 MW)	Heptane
USCG-18	Pan fire on side of simulated engine (0.5 m^2 ~ 1.6 MW)	Heptane
USCG-19	Pan fire on side of simulated engine (0.1 m^2 ~ 250 kW)	Heptane

4.4.4 Fire Configurations

The spray fires were produced using the pressured fuel system shown in Figure 10. The system was located on the main deck just aft of the test compartment. The system was designed to operate at low pressures (a storage tank pressure range of 340-510 kPa (50-75 psi) and an approximate nozzle pressure ranging from 205-340 kPa (30-50 psi)). These pressures were lower than those stated in the IMO test protocol, but previous studies [2] have shown insignificant variations in extinguishment difficulties between spray fires of various pressures for a given heat release rate (fire size). The fuel system consisted of a 300 L (80.0 gal) storage tank filled with fuel and pressurized with nitrogen. The system was constructed of 13 mm (0.5 in.) stainless steel tubing and connected together with stainless steel compression fittings. The fuel system was controlled from the control room via solenoid valves. The Bete Fog Nozzle, Inc. "P" series nozzle was selected as the fuel spray nozzle for this evaluation. Model numbers P32, P40, P54, P80 and P120 were required for the five spray fires used in this test series. These nozzles were operated in the previously mentioned pressure ranges to produce the 0.6, 0.8, 1.0, 2.0 and 6.0 MW fires respectively.

The fuel pans were constructed of 3.2 mm (⅛ in.) steel plate with welded seams. In all pan fire tests, the pans contained a 2.5 cm (1.0 in.) water substrate and 5.0 cm (2.0 in.) of fuel. The pans were ignited manually using a torch. During the tests conducted with the higher flashpoint fuels (i.e., diesel and lubricating oil), 114 mL (4 oz) of heptane was used as an accelerant.

In each fire scenario, small fires referred to as "telltales" were located in the room to help provide an indication of mist concentrations throughout the space. These fires were small heptane pan fires which were manually ignited prior to the test. The pans were 5.0 cm (2.0 in.) in diameter, approximately 10.0 cm (4.0 in.) tall, and fueled with 114 mL (4 oz.) of heptane. These pans were located on two vertical arrays as shown in Figure 11. Each array consisted of a telltale located every 122 cm (4.0 ft) beginning 30 cm (1.0 ft) above the lower deck.

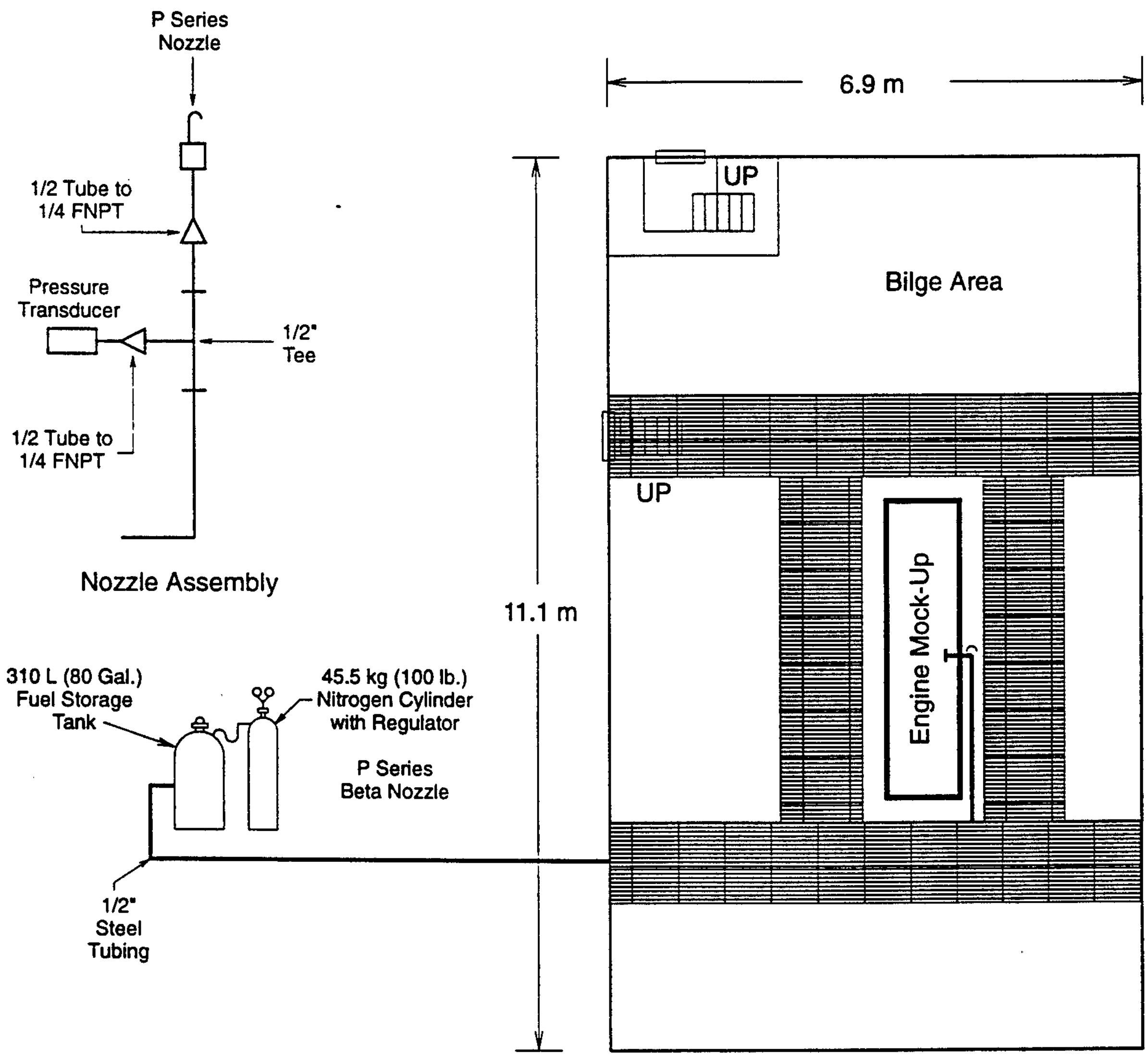


Figure 10. Spray Fire Fueling System

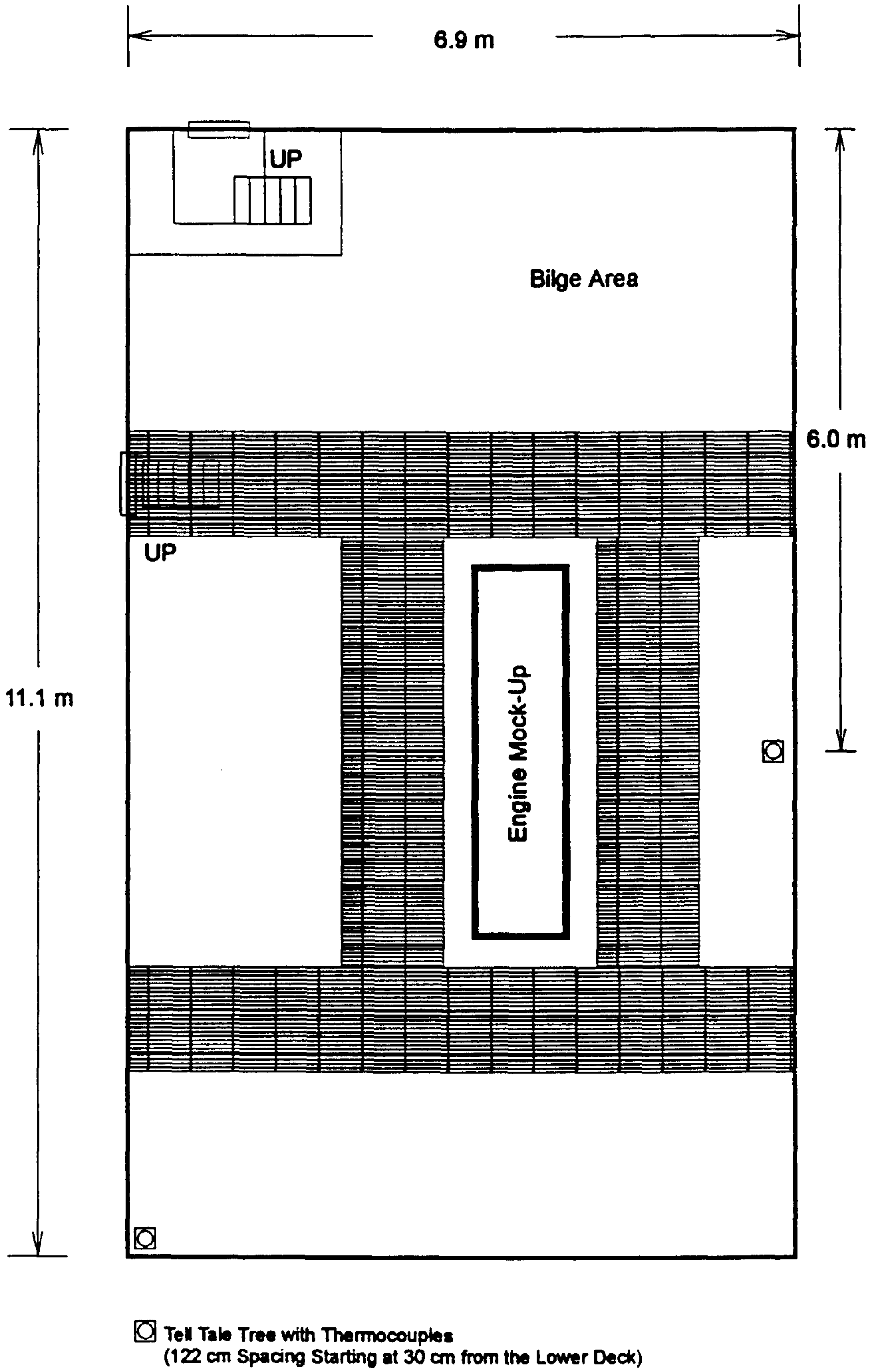


Figure 11. Tell Tale Fire Locations

5.0 INSTRUMENTATION

5.1 Water Mist System Instrumentation

The water mist system used during these tests was instrumented to measure both system pressures and total system flow rates as shown in Figure 12. A further description of the water mist system instrumentation is listed as follows.

5.1.1 Pressure Measurements

System pressures were measured at two locations: at a representative location in the pipe network and at the discharge manifold as shown in Figure 12. Setra Model 280E pressure transducers were used for this application. These transducers had a pressure range of 0-200 bar (0-3000 psi) with an accuracy of 0.1 percent full scale or 0.2 bar (3 psi).

5.1.2 System Flow Rate Measurements

The flow rate of the water mist system was measured using a paddle wheel type flow meter. The flow meter was located just upstream of the supply manifold providing water to either the high-pressure pumps for the high-pressure systems or to the pipe network itself for the low-pressure systems. The flow meter was sized to measure a range of flows from 50-500 Lpm (13-130 gpm) accurately.

5.2 Machinery Space Instrumentation

The machinery space was instrumented to measure both the thermal conditions in the space as well as CO, CO_2, and O_2. Instruments were installed to measure air temperatures at different elevations, fire temperature (to note extinguishment times), radiant and total heat flux, and compartment pressures. Data was collected using the USCG data acquisition system at a rate of one scan every six seconds. The instrumentation scheme is shown in Figure 13. A complete list of instruments and instrument locations can be found in Appendix B. A more detailed description of the instrumentation scheme is as follows.

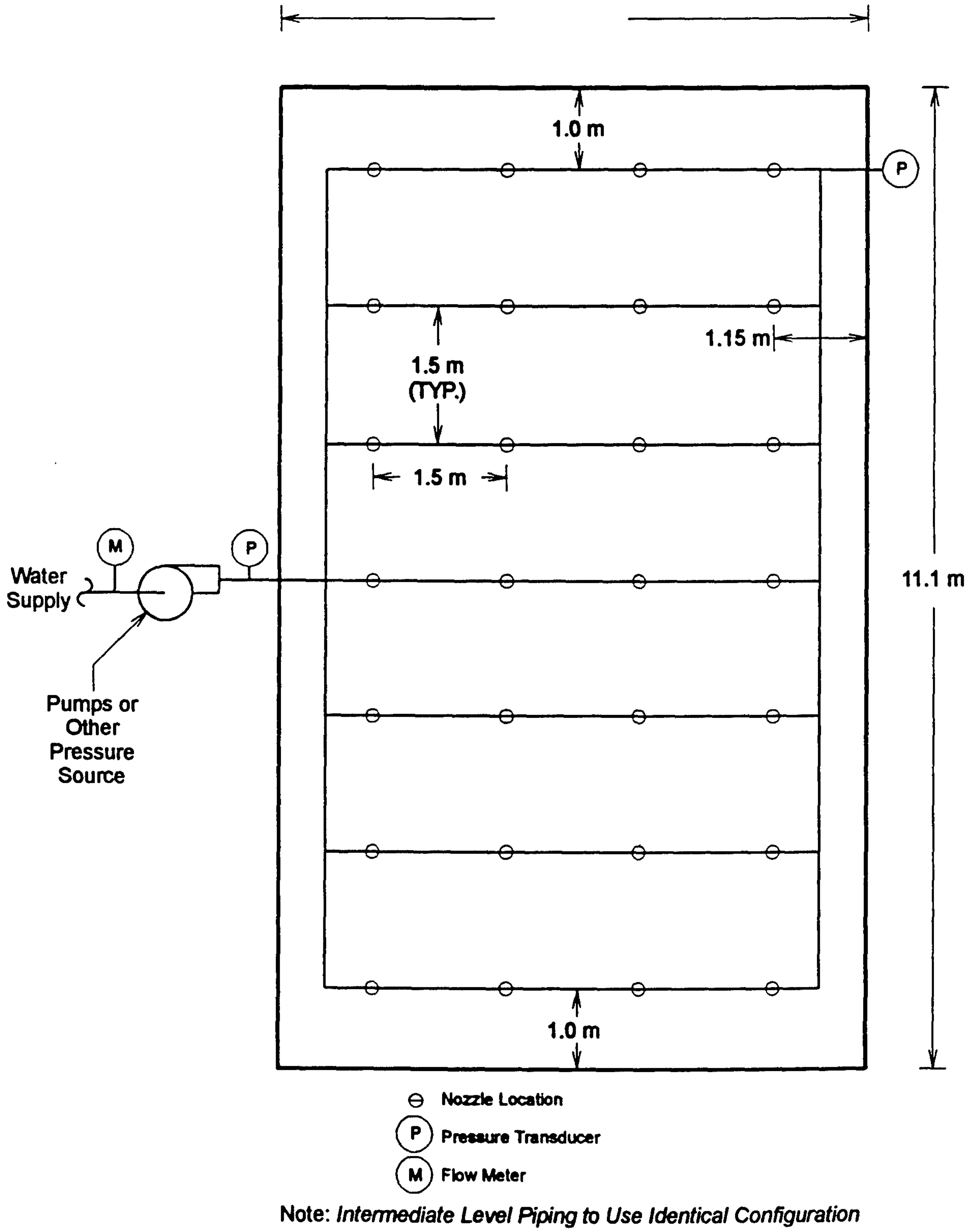


Figure 12. Water Mist System Instrumentation

5.2.1 Air Temperature Measurements

Three thermocouple trees were installed in the compartment. Each tree consisted of 12 thermocouples positioned at 61 cm (2.0 ft) increments starting 30 cm (1.0 ft) above the lower deck. Sixteen gauge, inconel-sheathed type-K thermocouples were used in this application.

5.2.2 Gas Concentration Measurements

Carbon monoxide, carbon dioxide, and oxygen concentrations were sampled at four elevations in the compartment. These measurements were made along the center line of the space 1.0 m (3.3 ft) aft of the forward bulkhead. The instruments were installed 1.5 m (5.0 ft) above the deck and spaced 1.5 m (5.0 ft) apart up to a height of 6.0 m (19.5 ft). Additional water traps were installed to assure that any water entrained into the sampling line was removed before the sample reached the analyzers. Note: the gas concentrations measured during these tests are "dry" and do not include any dilution effects of steam.

5.2.2.1 *Oxygen Concentration (Fire Location)*

An additional oxygen analyzer and movable sampling probe were installed for these tests. The additional sampling line was positioned adjacent to the base of the main fire source.

5.2.3 Heat Flux Measurements

Both radiant and total heat flux were recorded at four locations in the compartment. These transducers were installed on the centerline of the port bulkhead and spaced 1.5 m (5.0 ft) apart beginning 1.5 m (5.0 ft) above the lower deck. These instruments were Schmidt Boetler transducers manufactured by Medtherm Co. and had a range of 0-50 kW/m^2. Each radiometer was equipped with a 150° sapphire window.

5.2.4 Optical Density Meters

Three optical density meters were installed to measure the obscuration across the corner of the compartment during these tests shown in Figure 13. These measurements aided in estimating mist concentrations at various elevations in the compartment. The meters were installed at 2.0, 4.0 and 6.0 m (6.7, 13.1, and 19.7 ft) above the deck.

5.3 Fire Instrumentation

5.3.1 Flame Temperature

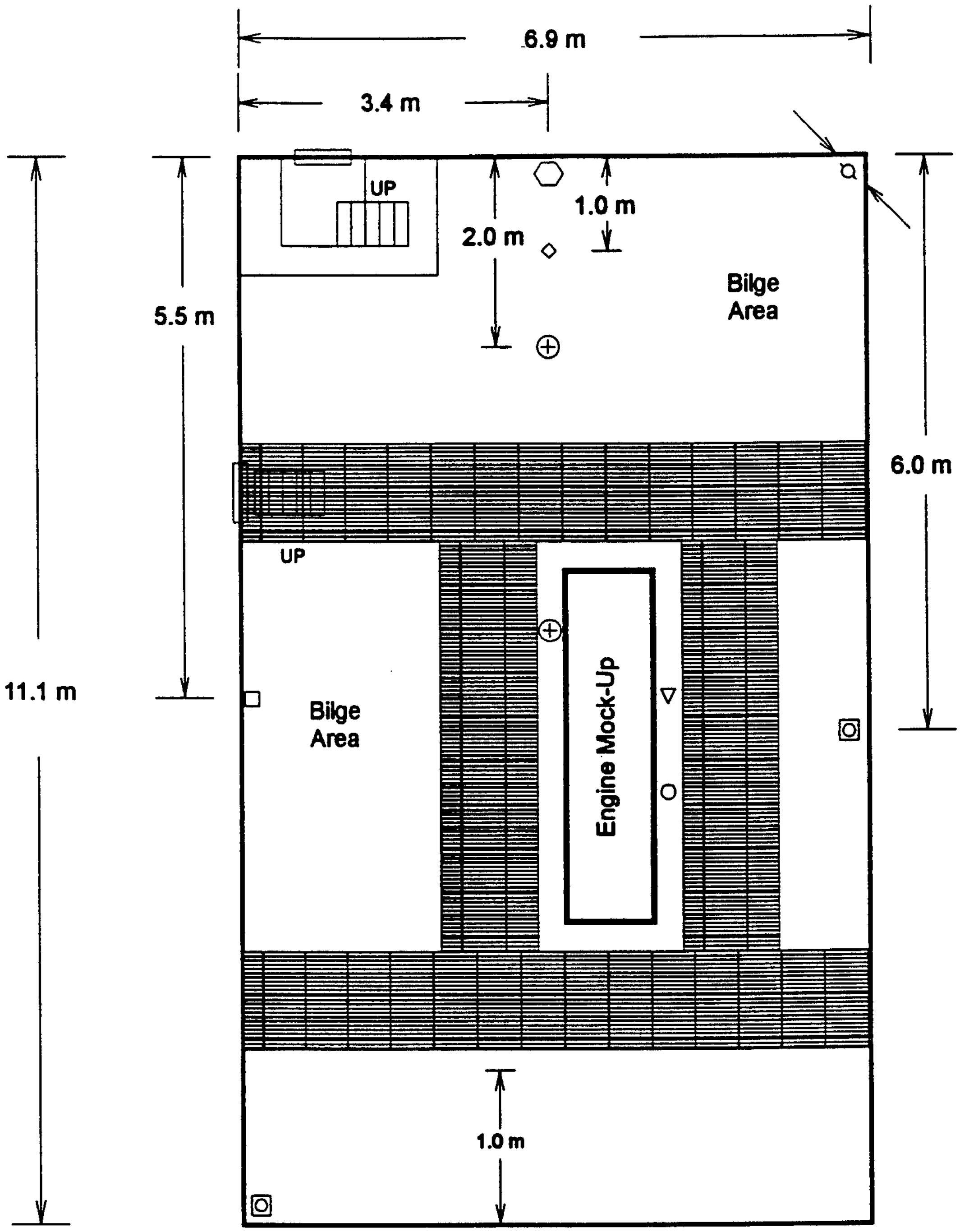
The temperature of each fire was measured to determine the extinguishment time of each fire. Thermocouples were located in the flame region of both the main fires and the telltale fires. These thermocouples were 16 gauge, inconel-sheathed type-K thermocouples.

5.3.2 Fuel Spray Nozzle Pressure

Fuel spray nozzle pressure was used to calculate the fuel flow rates in each test. Nozzle pressure was measured using a transducer manufactured by Setra Co. with a range of 0-680 kPa (0-100 psi). The energy release rate of each fire was calculated using the fuel flow rate and heat of combustion of the fuel. This assumes that all of the fuel was consumed with a 100 percent combustion efficiency.

5.4 Video Cameras

Four video cameras were used during this test series. The locations of these cameras are shown in Figure 14. Camera 1 (C1) was positioned primarily to monitor both arrays of telltales but could also view the main fire in all fire scenarios. Camera 2 (C2) focused on the telltale array located in the aft-port corner of the space. Windows/view ports (Plexiglass ≈ 1 cm thick) were installed at those locations in the bulkhead to allow the cameras to view the fires while remaining outside of the compartment. These two cameras were installed 1.5 m (5.0 ft) above the second deck. Two additional cameras were also positioned in the space during this test series



<u>Instrumentation</u>

⊕ Thermocouple Tree 61 cm Spacing @ 30 cm from Lower Deck (12 per Tree)
□ Radiometer & Total Heat Flux Pairs (1.75 m Spacing)
◇ Gas Sampling Tree (4 Sets - O_2, CO, CO_2 @ 1.5 m Spacing)
○ Oxygen Analyzer (Adjacent to Each Main Fire Location)
▣ Tell Tale Tree with Thermocouples (61 cm Spacing Starting @ 30 cm)
-○- Optical Density Meters (2.0 m, 4.0 m & 6.0 m)
▽ Fire Thermocouples

Figure 13. Machinery Space Instrumentation Plan

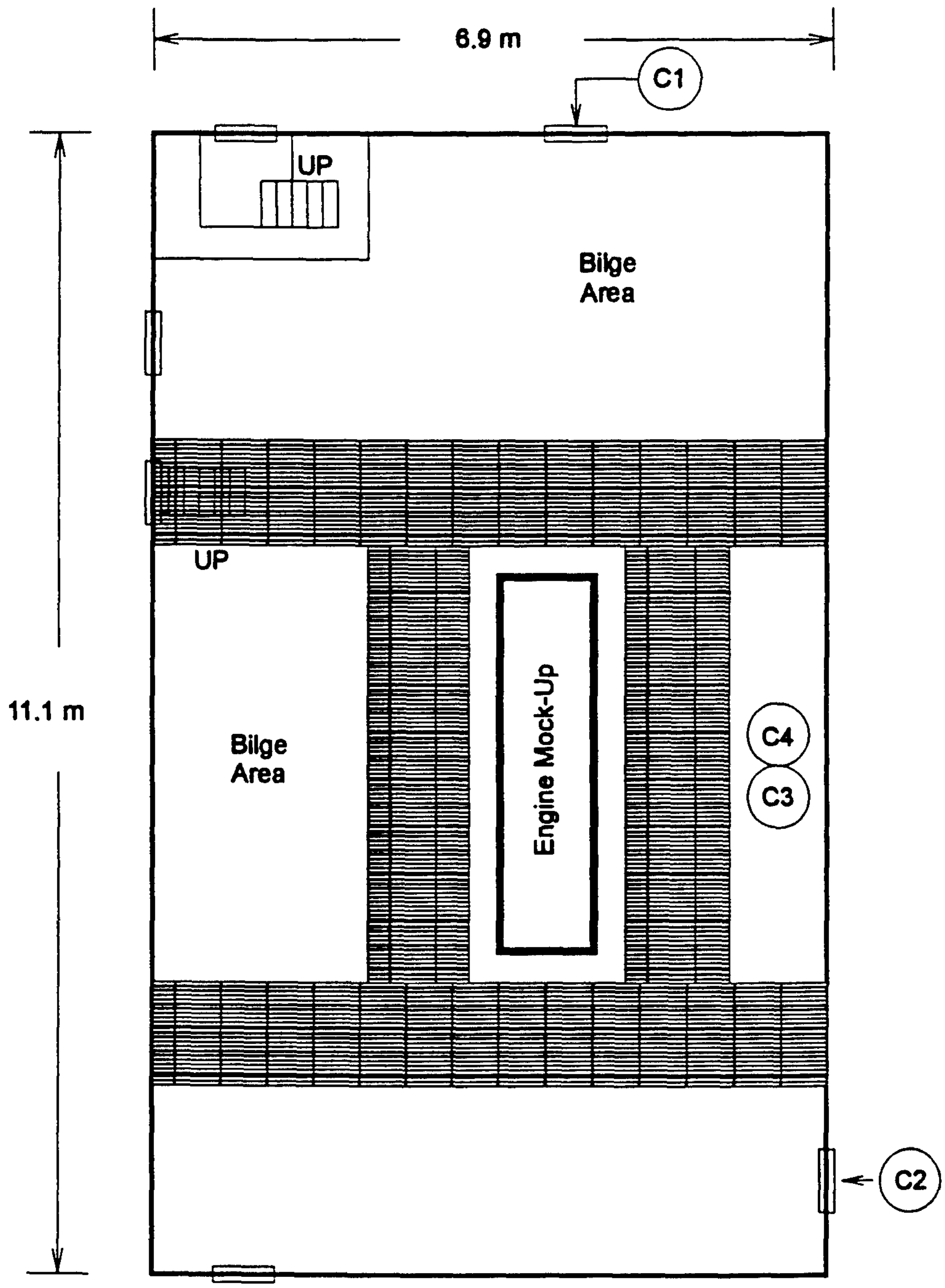


Figure 14. Camera Locations

(Cameras 3 and 4). Camera 3 was a standard video camera, and Camera 4 was an infrared video camera. These two cameras were installed in water-tight housings and mounted on tripods to allow them to be moved to different locations in the compartment. Cameras 3 and 4 were positioned to view the main fire during each test.

6.0 TEST OVERVIEW

6.1 Test Sequence

This experimental program consisted of seven individual evaluations, each designed to address a specific fire suppression issue. These evaluations are shown in Table 4 and are described in subsequent sections of this report.

6.1.1 Compartment Parameter Evaluation (size, shape and height)

The objective of these tests was to determine the effect the compartment parameters (size, shape and height) have on the fire extinguishing capabilities of the candidate water mist systems through comparison with the results obtained during U.S. Army Watercraft investigation using the standardized IMO enclosure. During this phase, the two primary systems (Spraying Systems and Grinnell AquaMist) were evaluated using both the IMO and Army fire tests (Table 2).

6.1.2 Nozzle Height Evaluation (5.0 m and 7.0 m heights)

The objective of these tests was to determine the effect the nozzle height has on the fire extinguishing capabilities of the candidate water mist systems. During this phase, the two primary systems (Spraying Systems and Grinnell AquaMist) were evaluated using the IMO and Army fire test scenarios.

6.1.3 Open Roof Vent Evaluation

The objective of these tests was to determine the effect that ventilation has on the fire suppression capabilities of the candidate water mist systems. These tests were conducted to add insight on the ability of water mist to protect extremely large (»500 m^3), open spaces where the suppression-enhancing effects of the enclosure are minimized. During these tests, the two primary systems were evaluated using both the IMO and Army fire test scenarios. The tests progressed from the easier open fires through the more difficult obstructed fires. Many fires were eliminated due to the results of previous tests.

6.1.4 System Performance Comparison Tests

The objectives of these tests were to evaluate and compare the system performances of five candidate water mist systems (Grinnell, Kidde Fenwal, Reliable, Securiplex and Spraying Systems). These systems cover the range of technologies (system types) currently available. The five systems were evaluated using both the IMO and Army fire tests. The nozzles were evaluated at a 7.0 m nozzle height.

6.1.5 Fire Extinguishment Difficulty Evaluation

The objective of these tests was to evaluate the ease or difficulty of extinguishment of a fire as a function of fire size and location. These tests were conducted using the Spraying Systems' nozzles (T series orifices) installed at the 7.0 m nozzle height. The fires consisted of both heptane spray and pan fires. Five heptane spray fire sizes (6.0, 7.0, 1.0, 0.8 and 0.6 MW) were evaluated at two locations in the space (high in the space on top of the mock-up, and low under the obstruction plate on the side of the mock-up). Three pan fire sizes (1.0 m^2, 0.5 m^2 and 0.1 m^2) were evaluated at three locations in the space (high on top of the mock-up, on the second deck low in the space, and under the obstruction plate on the side of the mock-up).

6.1.6 Increased Mist Discharge Rate Tests

The objective of these tests was to determine the effect that doubling the mist discharge rate has on the fire suppression characteristics of a candidate water mist system. During this evaluation, a total of 52 nozzles were installed in the compartment, thus almost doubling the number of nozzles and quantity of water discharged. Both the 5.0 and 7.0 nozzle grids were equipped with nozzles. It is assumed that the increased water discharge rate produced a higher mist concentration in the space and that the multiple levels of nozzles had little, if any, effect on the distribution of mist throughout the compartment. During these tests, the Spraying Systems' nozzles (T series orifices) were evaluated using a subset of the fires evaluated in the previous phase of this experimental program.

6.1.7 Increased Mist Discharge Rate - Open Roof Vent Evaluation

The objective of these tests was to re-evaluate the effect that ventilation has on the fire suppression characteristics of an overdesigned (high flow) candidate water mist system. These tests should further the knowledge on the protection afforded using water mist systems in larger spaces. During these tests the Spraying Systems' nozzles (T series orifices) were installed at both the 5.0 and 7.0 m elevations and evaluated against the fires evaluated in the previous phase of this investigation.

6.2 Test Procedures

The tests were initiated from the control room located on the 2nd deck. All key test personnel were located in the control room during each test with the following exceptions: two pump operators one located at each of the two pumping stations, the safety officer positioned outside the space on the main deck, and a technician located in the instrumentation trailer. Also, a fire fighting party was positioned on the main deck outside of the compartment. The pumps for the water mist system were started prior to the test. The machinery space ventilation system was activated prior to the start of the test. The telltale fires were ignited and the data acquisition system was activated. The data acquisition system collected background data for a minimum of five minutes prior to the ignition of the main fire. The test fires were ignited manually using a torch by a firefighter wearing protective clothing. The fires were allowed to burn freely for one minute before the ventilation system was secured and the mist system was activated. The mist system remained activated for a period of 15 minutes during each test or until all of the fires had been extinguished, whichever came first. At the completion of the 15-minute discharge, the mist system was secured marking the end of the test. The space remained off-limits until cleared by the safety officer and the test director.

Table 4. Test Matrix

System	Scenario	Nozzle Elevation	Roof Vent
(1) Compartment parameter evaluation			
Grinnell	13 IMO/5 ARMY	5.0 m	closed
Spraying Systems	13 IMO/5 ARMY	5.0 m	closed
(2) Nozzle height evaluation			
Grinnell	13 IMO/5 ARMY	7.0 m	closed
Spraying Systems	13 IMO/5 ARMY	7.0 m	closed
(3) Open Space Evaluation			
Grinnell	13 IMO/5 ARMY	5.0 m	open
Grinnell	13 IMO/5 ARMY	7.0 m	open
Spraying Systems	13 IMO/5 ARMY	5.0 m	open
Spraying Systems	13 IMO/5 ARMY	7.0 m	open
(4) System performance comparison			
*Grinnell	13 IMO/5 ARMY	7.0 m	closed
Kidde Fenwal	13 IMO/5 ARMY	7.0 m	closed
Reliable	13 IMO/5 ARMY	7.0 m	closed
Securiplex	13 IMO/5 ARMY	7.0 m	closed
*Spraying Systems	13 IMO/5 ARMY	7.0 m	closed
(5) Extinguishment difficulty evaluation			
Spraying Systems	5 spray fires/2 locations	7.0 m	closed
Spraying System	3 pan fires/3 locations	7.0 m	closed
(6) Increased mist discharge rate tests			
Spraying Systems	3 spray fires/2 locations	5.0 m & 7.0 m	closed
Spraying Systems	1 pan fire/3 locations	5.0 m & 7.0 m	closed
(7) Increased mist discharge rate - open space tests			
Spraying Systems	3 spray fires/2 locations	5.0 m & 7.0 m	open
Spraying Systems	1 pan fire/3 locations	5.0 m & 7.0 m	open

* Data collected from previous tests

7.0 RESULTS AND DISCUSSION

7.1 General Overview/Observations

The following discussion does not include the bilge fire scenarios (IMO-4, IMO-7, IMO-8, and IMO-13). The bilge scenarios were intentionally omitted due to the inability of the overhead water mist nozzles evaluated during the test series to extinguish these fires. It may be advantageous to protect the bilge areas with a separate extinguishing system having the ability to operate independently of the system installed in the main space. Further work is needed in this area.

Over 150 full-scale fire suppression tests were conducted during this test series. The extinguishment times were determined based on visual observations and on temperature measurements recorded in the flame during each test. An example of a typical flame temperature history is shown in Figure 15. During this test, the Grinnell AquaMist System extinguished the 6.0 MW diesel spray fire on top of the mock-up (IMO-1) in just under two minutes of mist system activation. Discussion of the specific tests and the findings of each phase of the test program are described in more detail in subsequent sections. The following observations were made concerning the overall performance of water mist technologies as applied to this application.

The primary result of interest pertains to the time required to extinguish these fires. The IMO requires that these fires must be extinguished in less than 15 minutes of system activation. In a majority of the tests, the candidate water mist systems required significant amounts of time (minutes) to extinguish the fire. This compares to the prominent gaseous halon alternatives that usually extinguish the fire within seconds (typically less than 30 seconds) of agent discharge. However, these shorter extinguishment times are for tests conducted in closed spaced. One would not expect gaseous agents, to be effective in an open space such as the IMO test enclosure. The extinguishment times recorded during these water mist tests range from just over one minute to as long as twelve minutes with some fires never extinguished. These times may be reduced by designing the water mist system around the specific hazard as illustrated during the U.S. Navy test program [3] or by reducing the ventilation. This would include installing nozzles at multiple

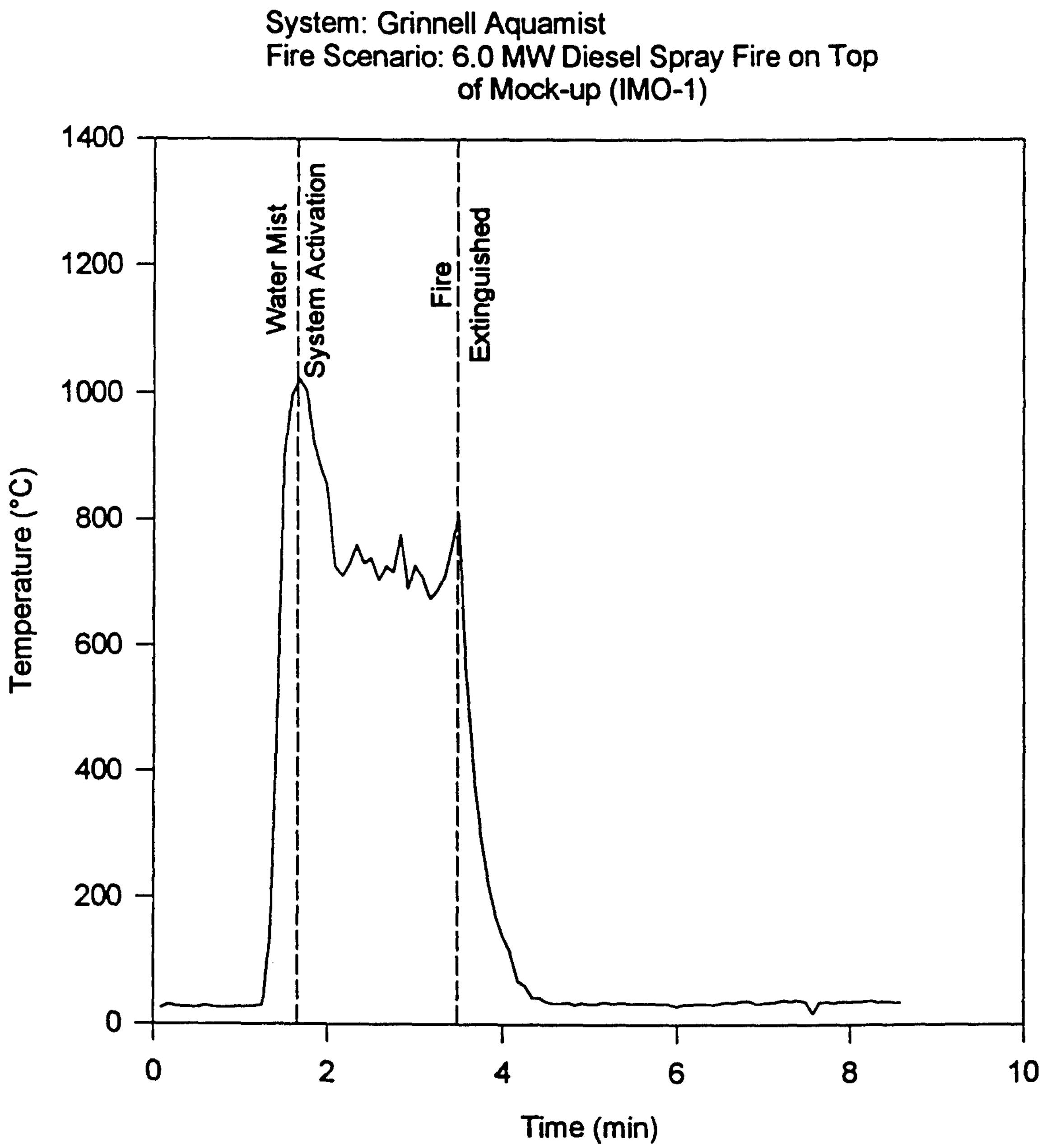
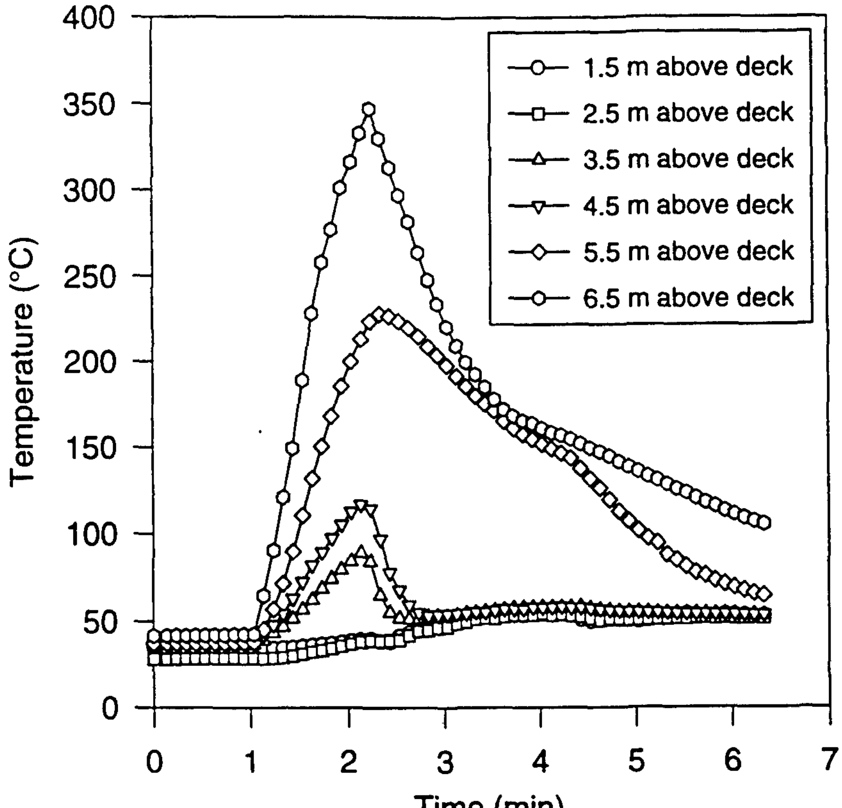


Figure. 15 - Typical Flame Temperature History elevations in the space as well as under obstructions. Reducing the vent losses by closing hatches leading into the compartment may also reduce the extinguishment times.

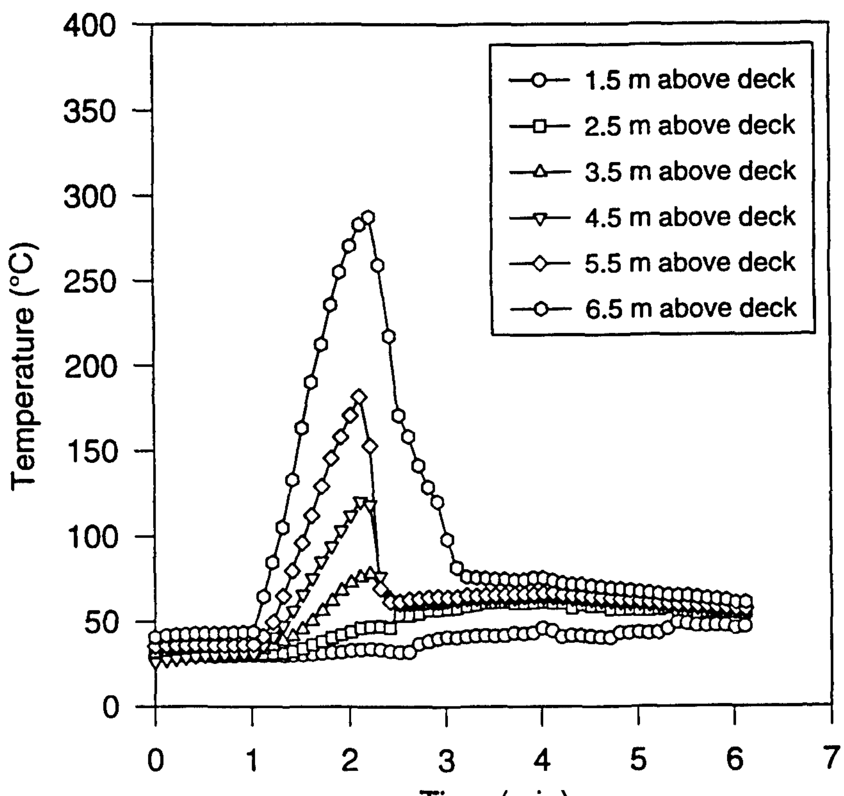
Although the candidate systems required minutes to extinguish these test fires, immediately after the water mist system was activated, the temperatures in the space were dramatically reduced. This reduction in temperature would help minimize the thermal damage to the space, prevent fire spread beyond the space, and aid in manual intervention. This temperature reduction was observed to be relatively equal for the five systems evaluated during this test series (independent of the type of system). While the mist system was activated, the temperatures in the space became uniform (no upper layer) and were reduced to between 50°-70°C (122°-158°F) depending on the fire scenario. The plots of the temperatures measured in the compartment for each of the tests conducted during this test series are found in Appendix C.

A typical compartment temperature is shown in Figure 16A & 16B. During these tests shown in Figures 16A and 16B, the Spraying Systems' nozzles were activated one minute after ignition of the main fire (6.0 MW heptane spray fire on the side of the mock-up (ARMY-5). The obstructed heptane spray fires were selected for this illustration because of their longer extinguishment times. Figure 16A is the temperature history in the space with the nozzles installed at an elevation of 5.0 m and Figure 16B at an elevation of 7.0 m. Immediately after system activation, the temperatures below the nozzles were reduced to 60°C (140°F) but the temperatures high in the space required over three minutes to be reduced to the temperatures measured elsewhere in the space. This was attributed to the lack of mist high in the space. When the nozzles were installed at a 7.0 m elevation, the entire space observed the same magnitude of temperature reduction.

An interesting phenomenon was also observed during the extinguishment of the obstructed spray fires. As the oxygen concentration in the space began to decrease, the spray fire flame began to behave differently. Initially, the flame became less turbulent. Once the oxygen concentration dropped below approximately 19.0 percent, the flame began to change from a bright yellow luminous flame to a bluish-purple flame. The flame was then observed to separate from the fuel spray source (blowoff). At this point, only the far edges of the fuel spray were burning. Many times during the test, the flame actually became completely detached from the



(a) 6.0 MW Heptane Spray Fire (Side)
5.0 m Nozzle Elevation



(b) 6.0 MW Heptane Spray Fire (Side)
7.0 m Nozzle Elevation

Figure 16. Typical Compartment Temperature Histories

fuel spray. The detachment and reattachment of the flame to the fuel spray continued until the fire was extinguished or until the test was terminated. This phenomenon was also observed for the unobstructed spray fires but depended on the water mist system being evaluated, the fire size, and fuel type.

As a general rule, the spray fires on the top of the engine mock-up (particularly IMO-1, IMO-2, IMO-5, IMO-12, and ARMY-1) are easier to extinguish than those located elsewhere in the space (IMO-3, IMO-6 and ARMY-5). This was attributed to two interrelated variables. First, a significant amount of mist reaches the fire due to their unobstructed nature and close proximity to the mist system nozzles. Secondly, oxygen concentration high in the compartment is reduced by the accumulations of the products of combustion and steam. This was most apparent during IMO-12 (1.0 MW heptane spray fire with reignition source). During this test, the prolonged pre-heating of the steel plate (to 350°C (662°F)) reduced the oxygen concentration in the space and increased the temperature of both the surface of the mock-up and the air in the space (a hot layer developed) as shown in Figure 17. Due to this reduction in oxygen and the steam produced by the elevated temperatures, these fires were extinguished almost immediately after mist system activation.

The obstructed fires (the fires located on the side of the mock-up) (IMO-3, IMO-4, IMO-6, and IMO-10) were significantly more difficult to extinguish than fires located elsewhere in the space as shown in Figure 18. In general, the two primary factors that contribute to the extinguishment of these obstructed fires are both the mist and oxygen concentration at the fire location. The mist concentration at a given location is a function of the flow rate and spray characteristics of the water mist system (droplet size distribution and spray momentum). The smaller droplet size/higher momentum nozzles usually demonstrate increased capabilities against obstructed fires. The oxygen concentration at the base of the fire with respect to time is a function of the size of the fire, compartment volume, and ventilation parameters of the space. The oxygen concentration in the space is also reduced due to the dilution effects of steam. Consequently, larger fires are usually easier to extinguish than smaller fires due to both a higher oxygen consumption rate and due to an increased steam production rate. This is illustrated by comparing the results of IMO-3 and IMO-6 (Figure 18). The larger spray fire (IMO-3, 6.0 MW),

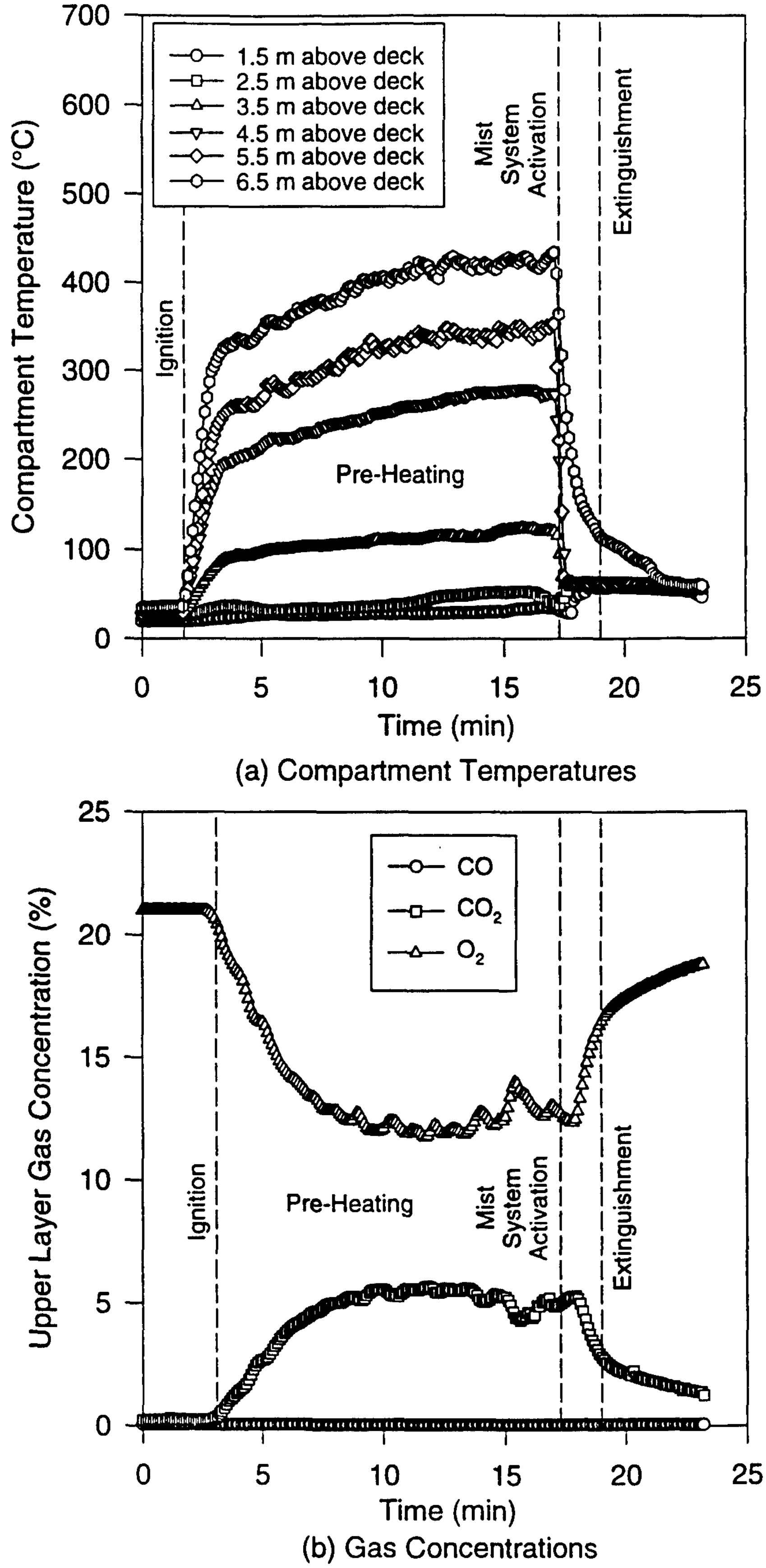


Figure 17. Compartment Conditions Observed During IMO-12

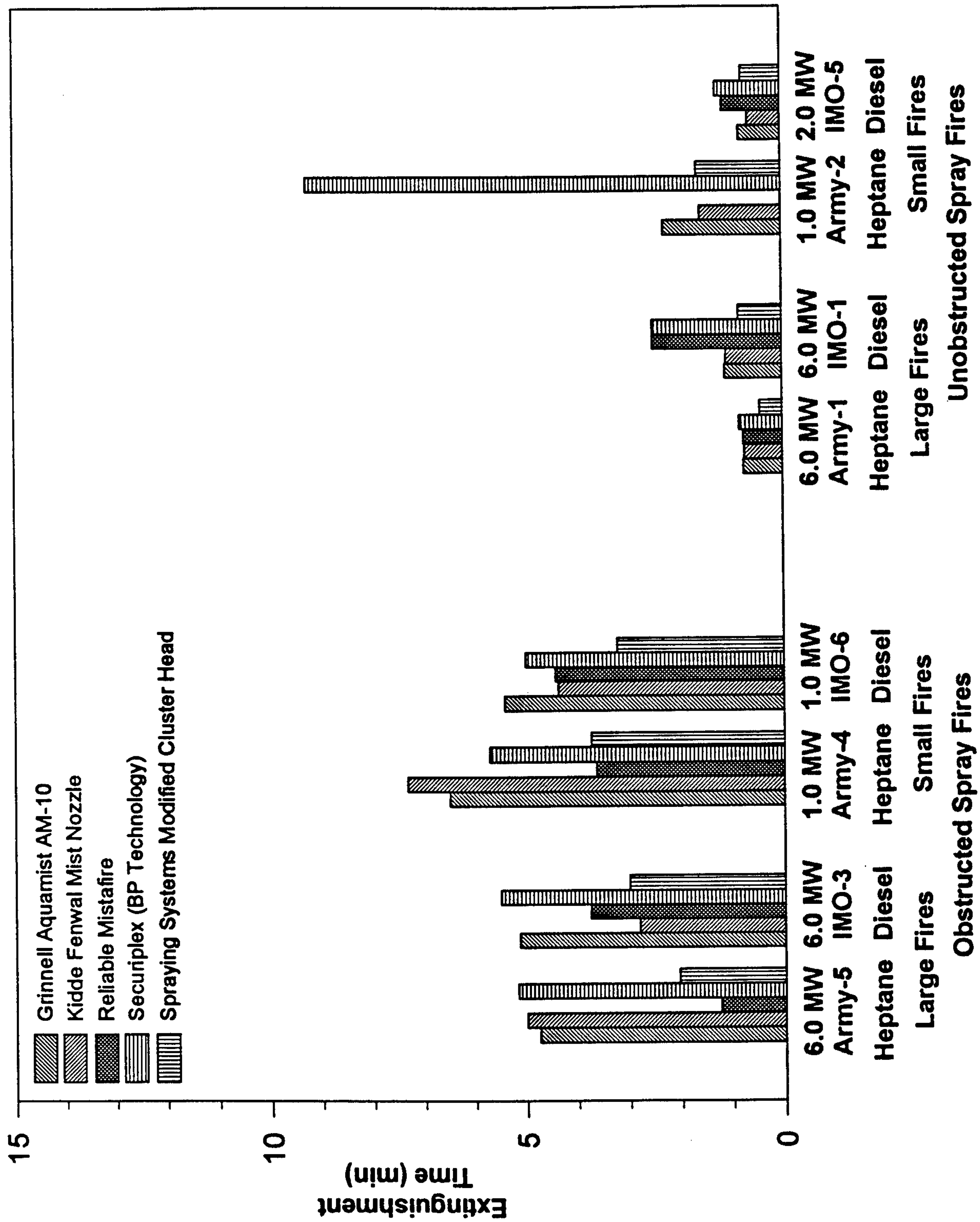


Figure 18. Extinguishment Comparison (obstructed vs. unobstructed)

was typically extinguished two or three minutes faster than the smaller spray fire (IMO-6, 1.0 MW). Larger fires also entrain more air than smaller fires, which could also contribute to these results.

Due to a lack of oxygen depletion and steam production, smaller fires are more difficult to extinguish than larger fires. This was illustrated by the poor performance exhibited by the water mist systems against the 0.5 m^2 (1.6 MW) (IMO-9) heptane pan fire and 1.0 MW spray fires located under the obstruction plate (IMO-6 and ARMY-4). As stated previously, the smaller fire usually required two to three minutes longer to extinguish. The 0.5 m^2 (1.6 MW) heptane pan fire and the 1.0 MW heptane spray fire located on the side of the mock-up were observed to distinguish the higher performance water mist systems from the lower performance systems. Only two systems were capable of extinguishing these two fires.

The large heptane pan fire on the top of the mock-up (IMO-10) was one of the more difficult fires to extinguish. Based on the results of the spray fire tests conducted on top of the mock-up, it was anticipated that the pan fire scenario would not pose a challenge to the candidate systems. However, the large pipe (simulating a manifold) located along the top of the mock-up combined with the high pan sides, presented a significant obstruction to the distribution of water mist. During the tests when the fire was not extinguished, the mist system extinguished the areas of the pool fire open to the mist, but could not extinguish the flames between the side of the pan and the obstruction. These small fires consequently kept spreading back across the fuel surface.

In general, the fires conducted with the lower flash point fuel [Heptane -4°C (25°F)] were more difficult to extinguish than those conducted with the higher flash point fuel [Diesel 52°C (126°F)]. During the tests conducted with the open roof vents. Many diesel fuel spray fires were extinguished that could not be extinguished using heptane as the fuel. The increased difficulty of lower flash point fuels is attributed to the high potential for reignition, the constant production of flammable vapor mixtures above the fuel surface in the absence of flame radiation, and the inability of water mist to cool the fuel surface below the flash point of the fuel. The ease/difficulty in extinguishment between the two fuels became less pronounced during the tests conducted using the standard vent configuration.

7.2 Compartment Parameter Evaluation

In general, the results of these tests are similar to those obtained during the U.S. Army Watercraft test program [2]. A comparison of the extinguishment times and oxygen concentration in the space between the two programs is shown in Table 5. The extinguishment times for the fires located on top of the mock-up were comparable in the two test series. The only significant variation occurred during the fire tests conducted on the side of the mock-up. The extinguishment times measured for the fires conducted on the side of the mock-up were as a rule significantly less for this test series than were measured during the Army investigation. This reduction in extinguishment time appears to be related to the oxygen concentration in the space, the mist losses out of the vent opening, and the increased height of the compartment. As identified during the Army tests and consistent with these tests, the obstructed fires were extinguished when the oxygen concentration at the base of the fire dropped below 16 percent for the Grinnell AquaMist system, and below 19 percent for the Spraying Systems' nozzles. The oxygen concentration in the space was observed to decrease at a faster rate during these tests than was observed during the Army tests, thus producing faster extinguishment times. This was attributed to the location of the vent opening with respect to the weather. During the Coast Guard tests, the vent opening was located on the second deck inside the ship. Confinement of the mist and products of combustion inside of the ship increases the likelihood that the mist and products of combustion could be entrained back into the compartment. This re-entrainment would significantly lower the oxygen concentration in the space. In the Army tests, the vent was open to the weather allowing combustion gases to escape and fresh air to enter. The height of the space may have also contributed to the decrease in extinguishment times. The increased height of the space provides a significant volume in which to contain the hot layer. The heat and products of combustion stored in this hot layer may aid in the production of steam and consequently decrease the extinguishment times. Since the Army vent was opened to the weather, it is also more susceptible to variations caused by ambient winds. The net result of these effects allowed the Grinnell AquaMist system to extinguish two fires during this test series which were not extinguished during the Army test series (3 m^2 (10.0 MW) heptane pan fire on top of the mock-up and 1.0 MW heptane spray fire on the side of the mock-up).

Table 5. Compartment Parameter Evaluation Results

Fire Scenario	Extinguishment Times (min:sec) (*Oxygen Concentrations at the Base of the Fire (%))			
	Grinnell AquaMist		Spraying Systems	
	ARMY 4.5 m IMO Vent	USCG 5.0 m IMO Vent	ARMY 4.5 m IMO Vent	USCG 5.0 m IMO Vent
1.0 MW Heptane spray fire on top of simulated engine	3:30 (18.4)	4:08 (20.5)	3:00 (18.8)	2:18 (19.5)
1.0 MW Heptane spray fire on top with reignition source of simulated engine	1:42 (19.8)	2:00 (19.25)	2:50 (19.6)	0:10 (18.5)
2.0 MW Heptane spray fire on top of simulated engine	3:00 (17.3)	2:32 (17.75)	2:10 (18.6)	1:00 (19.0)
2.0 MW Diesel spray fire on top of simulated engine	1:12 (17.7)	0:28 (19.4)	1:36 (18.8)	1:57 (18.5)
6.0 MW Heptane spray fire on top of simulated engine	1:52 (16.8)	1:55 (18.0)	2:15 (16.7)	0:40 (18.75)
6.0 MW Diesel spray fire on top of simulated engine	1:24 (17.0)	1:07 (18.25)	1:42 (16.8)	1:27 (19.3)
3 m^2 (10.0 MW) Heptane pan fire on top of simulated engine	NO (15.5)	6:20 (15.0)	2:30 (18.75)	0:30 (18.2)
Heptane flowing fuel fire from top of mock-up	NO (--)	NO (--)	9:20 (--)	N/A (--)
1.0 MW Heptane spray fire on side of simulated engine	NO (16.6)	10:36 (12.0)	8:45 (17.8)	4:09 (17.9)
1.0 MW Diesel spray fire on side of simulated engine	9:03 (15.9)	7:27 (14.5)	3:43 (18.2)	3:00 (18.0)
6.0 MW Heptane spray fire on side of simulated engine	10:07 (14.5)	5:10 (--)	4:30 (17.8)	2:16 (16.9)
6.0 MW Diesel spray fire on side of simulated engine	7:16 (15.6)	4:35 (--)	2:26 (18.0)	2:59 (17.5)
0.1 m^2 (250 kW) Heptane on top of bilge plate centered under exhaust plate	NO (20.8)	NO (20.8)	4:15 (20.8)	NO (20.8)
0.5 m^2 Heptane central under mock-up	NO	NO	NO	N/A
0.5 m^2 Oil central under mock-up	NO	NO	NO	NO

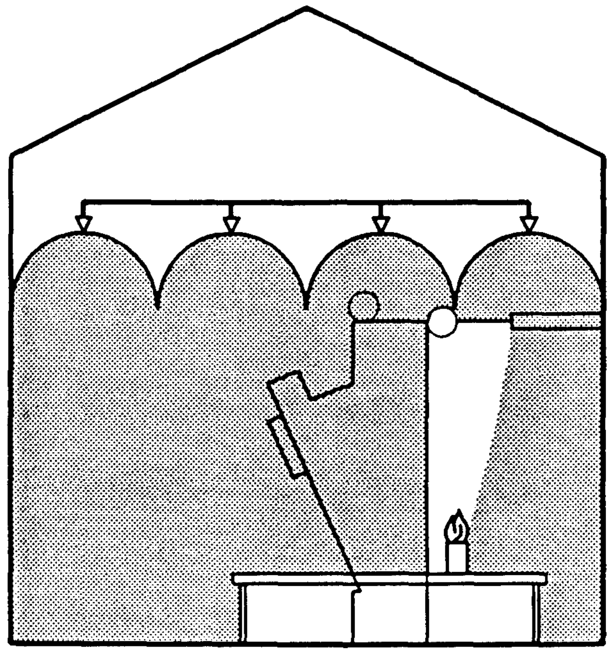
Notes: NO = No extinguishment during the 15-minute discharge
N/A = Not tested (These tests were eliminated due to the results of other tests. The results are assumed to be no extinguishment.)
-- = No data recorded
* = Oxygen concentration measured at the base of the fire at extinguishment

The only other significant variation in these results occurred against the 0.1 m^2 (250 kW) heptane pan fire located on the side of the mock-up (IMO-9). During the Army tests, the Spraying Systems' nozzles were the only system capable of extinguishing this fire but was unable to extinguish this fire during the Coast Guard tests. This variation in results may be related to compartment geometry. During the Army tests, the mock-up was positioned in the center of the space (Figure 19) with two rows of nozzles located between the bulkhead and the engine mock-up. This arrangement provided sufficient distribution of mist under the obstruction plate to extinguish the fire. During the Coast Guard tests, the end row of nozzles was located directly above the obstruction plate allowing only limited amounts of mist to reach the fire (Figure 19). The presence of a grated catwalk between the obstruction plate and the starboard bulkhead may have also reduced the amount of mist reaching the fire.

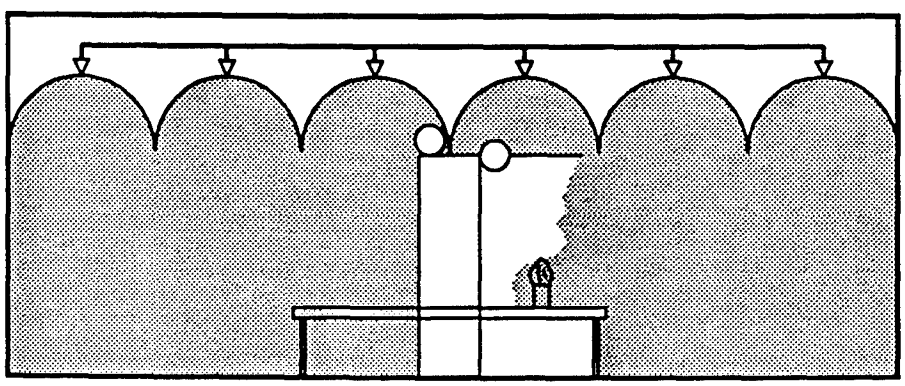
Midway through the test series, a revision was made to the test protocol by FP40. The revision consisted of replacing the 0.1 m^2 pan (IMO-9) fire with a 0.5 m^2 pan fire (both using heptane as the fuel). The hazard associated with the small pan fire was determined to be insignificant and thus abandoned for the larger fire. As a result of the increased fire size (1.6 MW vs. 0.25 MW) and the resulting oxygen depletion, two systems (Kidde Fenwal and Spraying Systems) were now capable of extinguishing this fire. These fires were extinguished approximately 12 minutes after mist system activation. The results of these tests further support the conclusion that smaller fires are more difficult to extinguish than larger fires.

7.3 Nozzle Height Evaluation

The results of the nozzle height evaluation are listed in Table 6. In general, both systems observed increased performance with the nozzles installed at the 7.0 m height as opposed to the 5.0 m height. There are two primary factors that could contribute to this increase in performance: mist uniformity and increased steam production. In the areas close to the nozzle, the spray patterns of the mist have definite shapes related to their distribution configuration. At increased distance from the nozzles, mist from adjacent nozzles mixes to form a more homogeneous concentration, thus eliminating any areas of lower mist concentration. This increased uniformity of the mist concentration may have been a factor in reducing the extinguishment times between the 5.0 m and 7.0 m nozzle heights especially for the fires located on top of the mock-up.



U.S. Coast Guard Tests



U.S. Army Watercraft Tests

Figure 19. U.S. Army Watercraft and U.S. Coast Guard Test Compartment Comparison (Respect to Fires on the Side of the Mock-up)

Table 6. Nozzle Height Comparison Results

Fire Scenario	Extinguishment Times (min:sec) (*Oxygen Concentrations (%))			
	Grinnell AquaMist		Spraying Systems	
	USCG 5.0 m IMO Vent	USCG 7.0 m IMO Vent	USCG 5.0 m IMO Vent	USCG 7.0 m IMO Vent
1.0 MW Heptane spray fire on top of simulated engine	4:08 (20.5)	2:17 (19.2)	2:18 (19.5)	1:38 (18.75)
1.0 MW Heptane spray fire on top with reignition source of simulated engine	2:00 (19.25)	0:20 (19.5)	0:10 (18.5)	0:26 (18.5)
2.0 MW Heptane spray fire on top of simulated engine	2:32 (17.75)	1:18 (17.75)	1:00 (19.0)	1:05 (18.75)
2.0 MW Diesel spray fire on top of simulated engine	0:28 (19.4)	0:48 (18.75)	1:57 (18.5)	0:45 (19.25)
6.0 MW Heptane spray fire on top of simulated engine	1:55 (18.0)	0:45 (17.75)	0:40 (18.75)	0:26 (18.0)
6.0 MW Diesel spray fire on top of simulated engine	1:07 (18.25)	1:06 (19.25)	1:27 (19.3)	0:50 (19.5)
3 m^2 (10.0 MW) Heptane pan fire on top of simulated engine	6:20 (15.0)	NO (17.0)	0:30 (18.2)	6:35 (18.5)
Heptane flowing fuel fire from top of mock-up	NO (--)	N/A (--)	N/A (--)	N/A (--)
1.0 MW Heptane spray fire on side of simulated engine	10:36 (12.0)	6:30 (15.0)	4:09 (17.9)	3:44 (17.0)
1.0 MW Diesel spray fire on side of simulated engine	7:27 (14.5)	5:25 (15.5)	3:00 (18.0)	3:13 (17.25)
6.0 MW Heptane spray fire on side of simulated engine	5:10 (--)	4:45 (15.0)	2:16 (16.9)	2:03 (16.75)
6.0 MW Diesel spray fire on side of simulated engine	4:35 (--)	5:08 (15.5)	2:59 (17.5)	3:06 (18.0)
0.1 m^2 (250 kW) Heptane on top of bilge plate centered under exhaust plate	NO (20.8)	NO (20.8)	NO (20.8)	NO (20.8)
0.5 m^2 (1.6 MW) Heptane central under mock-up	NO	NO	N/A	N/A
0.5 m^2 (1.6 MW) Oil central under mock-up	NO	NO	NO	NO

Notes: NO = No extinguishment during the 15-minute discharge
N/A = Not tested (These tests were eliminated due to the results of other tests. The results are assumed to be no extinguishment.)
-- = No data recorded
* = Oxygen concentration measured at the base of the fire at extinguishment

A more likely candidate, however, is steam production. With the nozzles installed at an elevation of 5.0 m, there was a 2-3 m space between the nozzles and the top of the compartment. A majority of the hot layer was located in this region. Thus, the nozzles were installed in or below the hot layer depending on the depth of the layer. When the nozzles were installed at a 7.0 m elevation, the mist must penetrate the hot layer in order to reach the fires. As the mist passes through the hot layer, the layer was rapidly cooled to below 70°C (158°F). The magnitude of this cooling effect was independent of the mist system being evaluated. The energy absorbed during this cooling process converts some of the mist to steam aiding in extinguishment of the fire due to oxygen dilution. As the gases continued to cool, the steam condenses back into small droplets which effectively increases the fraction of fine drops in the compartment. On the negative side, the penetration of the hot layer may reduce the momentum of the spray.

The reduction in momentum is illustrated when comparing the results of the 3 m^2 heptane pan fire located on top of the mock-up (Army-3). The 3 m^2 heptane pan has an estimated heat release rate of over 10 MW, the largest fire evaluated during the test series. During these tests, the systems installed at the 5.0 m elevation significantly out-performed the systems installed at the 7.0 m elevation. The lack of momentum associated with the nozzles installed at the 7.0 m elevation prevented the mist from mixing/moving around the pipe obstruction on top of the mock-up, thus preventing the total extinguishment of the fire.

7.4 Open Roof Vent Evaluation

The results of the tests conducted with the open roof vent are listed in Table 7. During these tests, 25 percent of the overhead of the space was removed. The net result of opening a large section of the overhead was a dramatic reduction in capabilities for all of the water mist systems evaluated during this test series.

There are three variables which contribute to the reduction in performance resulting from the increased ventilation: mist concentration, oxygen depletion, and steam generation. Increasing the size of the vent increases the mist losses out the vent opening and decreases the mist concentration in the space. Oxygen depletion effects are also reduced/eliminated.

Table 7. Open Space Evaluation Results

Fire Scenario	Extinguishment Times (min:sec) (*Oxygen Concentrations (%))							
	Grinnell AquaMist (340 Lpm, 12 bar, 4.4 Lpm/m^2)				Spraying Systems (170 Lpm, 70 bar, 2.2 Lpm/m^2)			
	USCG 5.0 m IMO Vent	USCG 7.0 m IMO Vent	USCG 5.0 m Roof Vent	USCG 7.0 m Roof Vent	USCG 5.0 m IMO Vent	USCG 7.0 m IMO Vent	USCG 5.0 m Roof Vent	USCG 7.0 m Roof Vent
1.0 MW Heptane spray fire on top of simulated engine	4:08 (20.5)	2:17 (19.2)	N/A (--)	N/A (--)	2:18 (19.5)	1:38 (18.75)	N/A (--)	N/A (--)
1.0 MW Heptane spray fire on top of reignition source of simulated engine	2:00 (19.25)	0:20 (19.5)	N/A (--)	N/A (--)	0:10 (18.5)	0:26 (18.5)	N/A (--)	NO (20.6)
2.0 MW Heptane spray fire on top of simulated engine	2:32 (17.75)	1:18 (17.75)	N/A (--)	N/A (--)	1:00 (19.0)	1:05 (18.75)	N/A (--)	NO (20.8)
2.0 MW Diesel spray fire on top of simulated engine	0:28 (19.4)	0:48 (18.75)	NO (20.8)	NO (20.8)	1:57 (18.5)	0:45 (19.25)	1:06 (20.8)	2:43 (20.2)
6.0 MW Heptane spray fire on top of simulated engine	1:55 (18.0)	0:45 (17.75)	NO (20.8)	NO (20.7)	0:40 (18.75)	0:26 (18.0)	NO (20.6)	2:01 (20.0)
6.0 MW Diesel spray fire on top of simulated engine	1:07 (18.25)	1:06 (19.25)	3:52 (20.8)	2:59 (20.5)	1:27 (19.3)	0:50 (19.5)	0:26 (20.5)	1:13 (20.2)
3 m^2 (10.0 MW) Heptane pan fire on top of simulated engine	6:20 (15.0)	NO (17.0)	NO (20.6)	N/A (--)	0:30 (18.2)	6:35 (18.5)	NO (20.5)	NO (20.6)
Heptane flowing fuel fire from top of mock-up	NO (--)	N/A (--)	N/A (--)	N/A (--)	N/A (--)	N/A (--)	N/A (--)	N/A (--)
1.0 MW Heptane spray fire on side of simulated engine	10:36 (12.0)	6:30 (15.0)	N/A (--)	N/A (--)	4:09 (17.9)	3:44 (17.0)	N/A (--)	N/A (--)
1.0 MW Diesel spray fire on side of simulated engine	7:27 (14.5)	5:25 (15.5)	N/A (--)	N/A (--)	3:00 (18.0)	3:13 (17.25)	N/A (--)	N/A (--)
6.0 MW Heptane spray fire on side of simulated engine	5:10 (--)	4:45 (15.0)	N/A (--)	N/A (--)	2:16 (16.9)	2:03 (16.75)	N/A (--)	N/A (--)
6.0 MW Diesel spray fire on side of simulated engine	4:35 (--)	4:08 (15.5)	NO (20.2)	NO (20.4)	2:59 (17.5)	3:06 (18.0)	NO (20.7)	NO (20.6)

Notes:
NO = No extinguishment during the 15-minute discharge
N/A = Not tested (These tests were eliminated due to the results of other tests. The results are assumed to be no extinguishment.)
-- = Data not recorded
* = Oxygen concentration measured at the base of the fire at extinguishment

Oxygen depletion has been identified as one of the contributing factors in extinguishing shielded/obstructed fires. The Army investigation demonstrated that fires located in areas of lower mist concentration can still be extinguished with some help from oxygen depletion. An example of this are the spray fires located on the side of the mock-up. These fires are typically extinguished when the oxygen concentration at the base of the fire drops below 15-18 percent depending on the mist system being evaluated. During the tests with the open roof vent, the oxygen concentration remained at ambient conditions (21%) for the duration of the test.

Steam production and condensation may also be a contributing factor in extinguishment. The production of steam reduces the oxygen concentration in the space due to dilution effects. Dilution can occur on both a localized or global scale. This oxygen dilution is difficult to accurately measure using standard oxygen analyzers and, if quantified, would aid in the better understanding of the extinguishment process. Additionally, steam mixes through the space like a gas increasing the mist system's capabilities against shielded/obstructed fires. As the steam cools, it condenses back into mist (very small droplets) thus effectively changing the drop size distribution in the space. During the tests conducted with the open roof vent, a significant amount of heat is lost through the overhead roof vent, thus preventing the formation of a hot layer which aids in steam production. Also, any steam that is produced on a localized scale is lost out the vent opening.

Consequently, due to the amount of mist lost out the vent, the lack of oxygen depletion in the space and the lack of steam production, the two systems evaluated during these tests were only capable of extinguishing a limited number of the 13 IMO tests with the open roof vent. The Grinnell AquaMist Systems was capable of extinguishing only the 6.0 m diesel spray fire on top of the mock-up. This fire was successfully extinguished with the system installed at both the 5.0 MW and 7.0 m elevations. The Spraying Systems' nozzles were capable of extinguishing both the 6.0 MW and 2.0 MW diesel spray fires located on top of the mock-up with the nozzles installed at each of the two elevations (5.0 m and 7.0 m). The heptane spray fires were significantly more difficult to extinguish than the diesel fuel fires. Only one heptane spray fire was extinguished with the roof vents open. The spraying systems nozzles were capable of extinguishing the 6.0 MW heptane spray fire. This further illustrates that higher flashpoint fuels are easier to extinguish than lower flashpoint fuels.

During the tests with the open roof vent, only the large diesel fuel spray fire (6.0 MW) located on top of the mock-up were extinguished consistently. The larger fires were presumed to be easier to extinguish due to higher entrainment rates and greater localized oxygen depletion effects such as consumption of oxygen by the fire and greater steam production. Based on the measurements recorded in the space (oxygen remained near ambient concentration (above 20%)), any oxygen depletion effects aiding in the extinguishment of the fires with an open roof vent must have occurred on a localized scale.

The data may also illustrate the need for spray momentum not only to penetrate the plume, but also in this configuration, to prevent the mist from being carried out of the compartment by the thermal updraft created by the fire. This is illustrated by the superior performance of the Spraying Systems' nozzle installed at the 5.0 m elevation compared to the 7.0 m installation. The momentum characteristics associated with the larger drops produced by the Grinnell AquaMist System must have been adequate to negate these effects. This is illustrated by the similarity of the results of the tests conducted at both the 5.0 m and 7.0 m nozzle elevations.

7.5 System Performance Comparison Evaluation

The extinguishment times recorded during the system performance evaluation are listed in Table 8. The system performance evaluation was conducted with the nozzles installed at an elevation of 7.0 m. An evaluation of the performance of each system is described in the following sections.

7.5.1 Grinnell AquaMist

The Grinnell AquaMist system is a single-fluid low-pressure system that operates at a pressure of 12 bar (175 psi). At this pressure, the individual nozzles flow approximately 12 Lpm (3.1 gpm) producing a total system flow rate of 340 Lpm (90 gpm). This flow rate corresponds to a nominal application rate of 4.4 Lpm/m^2 (0.11 gpm/ft^2), the highest application rate evaluated during the test series.

Table 8. System Performance Comparison Test Results

Fire Scenario	Extinguishment Times (min:sec) / (*Oxygen Concentration (%))				
	Grinnell AquaMist 340 Lpm; 12 bar; 4.4 Lpm/m²	Kidde-Fenwal 315 Lpm; 12 bar 4.1 Lpm/m²	Reliable 254 Lpm; 70 bar 3.3 Lpm/m²	Securiplex 140 Lpm; 5.5 bar 1.8 Lpm/m²	Spraying Systems 170 Lpm; 70 bar 2.2 Lpm/m²
1.0 MW Heptane spray fire on top of simulated engine	2:17 (19.2)	1:34 (18.5)	N/A	9:16 (18.1)	1:38 (18.8)
1.0 MW Heptane spray fire on top of reignition source of simulated engine	0:20 (19.5)	--	0:30 (17.0)	--	0:26 (18.5)
2.0 MW Heptane spray fire on top of simulated engine	1:18 (17.8)	0:50 (18.4)	1:36 (18.3)	1:10 (18.2)	1:05 (18.8)
2.0 MW Diesel spray fire on top of simulated engine	0:48 (18.8)	0:38 (19.4)	1:07 (19.5)	1:15 (18.9)	0:45 (19.3)
6.0 MW Heptane spray fire on top of simulated engine	0:45 (17.8)	0:44 (18.1)	0:45 (19.5)	0:50 (17.8)	0:26 (18.0)
6.0 MW Diesel spray fire on top of simulated engine	1:06 (19.3)	1:05 (20.0)	2:30 (19.5)	2:30 (19.0)	0:50 (19.5)
3 m² (10.0 MW) Heptane pan fire on top of simulated engine	NO (17.0)	6:30* (17.7)	0:45* (19.5)	0:50* (18.5)	6:35 (18.5)
Heptane flowing fuel fire from top of mock-up	N/A	N/A	N/A	N/A	N/A
1.0 MW Heptane spray fire on side of simulated engine	6:30 (15.0)	7:20 (16.9)	3:38 (17.5)	5:43 (18.2)	3:44 (17.4)
1.0 MW Diesel spray fire on side of simulated engine	5:25 (15.5)	4:22 (17.0)	4:25 (17.5)	5:00 (18.3)	3:13 (17.3)
6.0 MW Heptane spray fire on side of simulated engine	4:45 (15.0)	5:00 (17.5)	1:15 (17.0)	5:10 (16.9)	2:03 (17.8)
6.0 MW Diesel spray fire on side of simulated engine	5:08 (15.5)	2:49 (17.5)	3:45 (17.8)	5:30 (18.0)	3:06 (18.0)
0.1 m² Heptane on top of bilge plate centered under exhaust plate	NO (21.0)	--	--	--	NO (21.0)
0.5 m² (1.6 MW) Heptane pan	--	12:42** (17.25)	NO** (19.0)	NO** (18.6)	11:20 (17.8)
0.5 m² (1.6 MW) Heptane central under mock-up	NO	N/A	N/A	N/A`	N/A
0.5 m² (1.6 MW) Oil central under mock-up	NO	N/A	N/A	N/A	NO

Notes: NO = No extinguishment during the 15-minute discharge
N/A = Not tested (These tests were eliminated due to the results of other tests. The results are assumed to be no extinguishment.
-- = Not tested
* = Oxygen concentration measured at the base of the fire at extinguishment
** = Large pan (0.5 m²)

As shown in Table 8, the AquaMist system was capable of extinguishing a majority of the fires. The system extinguished the unobstructed fires located on top of the mock-up within one to two minutes of system activation. These extinguishment times were comparable to the other systems evaluated during this test series. The limits of the AquaMist nozzles were revealed during the obstructed fire tests (fires located on the side of the mock-up). The AquaMist system was capable of extinguishing all of the obstructed spray fires but produced longer extinguishment times (approximately 5 - 6.5 minutes) than the other systems evaluated during this test series with a few exceptions. The extinguishment of the obstructed spray fires was observed to be related to the oxygen concentration at the base of the fire. For the AquaMist systems, the fires were extinguished when the oxygen concentration measured at the base of the fire dropped to 15.5 percent. This concentration is over one percent lower than the other systems evaluated. This suggests that the amount of mist reaching the fire or the efficiency of the mist reaching the fire is less for the AquaMist system than for the other systems evaluated during this test series.

The longer extinguishing times (approximately 5-6.5 minutes) for the obstructed fires are related to spray characteristics (larger $Dv_{50} \approx 500$ microns) of the AquaMist system. These larger droplets have limited capabilities against partially obstructed fires due to high losses associated with gravity (fall-out rates/terminal velocities). The AquaMist system also failed to extinguish the 0.1 m^2 (250 kW) heptane pan fire (IMO-9) located under the obstruction plate on the side of the mock-up. This small pan fire could not be extinguished with the amount of mist reaching the fire, and the fire was too small to deplete the oxygen concentration in the space to the previously mentioned 15.5 percent (the oxygen concentration remained at 21 percent, see Table 8). After conducting the evaluation of the Grinnell AquaMist System, the IMO test protocol was revised, and the 0.1 m^2 pan fire was replaced with a 0.5m^2 pan fire. This larger fire would have depleted the oxygen in the space and could have possibly been extinguished by this system. The AquaMist system could also not extinguish the 3 m^2 (10.0 MW) heptane pan fire (Army-3) and pan fire/flowing fuel combination (IMO-10). The inability to extinguish these fires was attributed to the spray pattern characteristics of the nozzle(s). The nozzles produce a narrow spray pattern with a majority of the mist located under the nozzles and only minimum amounts of mist between two and four nozzles. After the system was activated, a majority of the pan fire was extinguished but the system could not extinguish the residual flames located in these areas of lower mist concentrations, and in obstructed areas under the exhaust manifold. These residual flames continually spread back across the fuel surface.

7.5.2 Kidde-Fenwal

The Kidde-Fenwal system is also a single-fluid low-pressure system that operates at a pressure of 12 bar (175 psi). At this pressure, the individual nozzles flow approximately 10 Lpm (2.5 gpm) producing a total system flow rate of 315 Lpm (83 gpm). This flow rate corresponds to an application rate of 4.1 Lpm/m^2 (0.1 gpm/ft^2) which is slightly less than the Grinnell AquaMist system.

The Kidde-Fenwal system performed very well during this test series. The system was capable of extinguishing all of the test fires within the fifteen minute time period required by the IMO test protocol. The superior performance exhibited by this system was attributed to the nozzle's ability to produce and distribute large quantities of small droplets ($Dv_{50} \approx 200 - 300$ microns). These small droplets, with the aid of the turbulence created by the fire mixed well throughout the compartment increasing the system's capabilities against the partially obstructed fires. As identified during the evaluation of the Grinnell AquaMist system, the extinguishment of the obstructed fires appears to be dependent on the oxygen concentration at the base of the fire. During the tests conducted with the Kidde Fenwal nozzles, the obstructed fires were extinguished when the oxygen concentration measured at the base of the fire dropped below 17.25 percent compared to 15.5% for the Grinnell AquaMist System. Based on the assumption that both mist concentration and oxygen depletion are required to extinguish a fire, these results suggest that more mist is reaching the fire for the Kidde Fenwal System than for the Grinnell AquaMist System. While both systems are still dependent on oxygen depletion to aid in extinguishment of these obstructed fires, the Kidde Fenwal is, however, less dependent on oxygen depletion than the Grinnell AquaMist system. The extinguishment times produced by this system ranged from approximately one minute for the spray fires located on top of the mock-up to between 3-7 minutes for the spray fires located on the side of the mock-up. The most challenging fire evaluated during this test series (IMO-9, 0.5 m^2 heptane pan fire) was extinguished by the Kidde Fenwal system in just under 13 minutes.

7.5.3 Reliable MistaFire

The Reliable MistaFire System is a single-fluid high-pressure system that has an operating pressure of 70 bar (1000 psi). At this pressure, the individual nozzles flow approximately 8.4 Lpm (2.2 gpm) producing a total system flow rate of 254 Lpm (67.0 gpm). This flow rate corresponds to an application rate of 3.3 Lpm/m^2 (0.08 gpm/ft^2). This application rate is approximately 60-80 percent of that used by the low pressure, single-fluid systems.

The Reliable MistaFire System was capable of extinguishing all of the fires evaluated in this test series with the exception of the obstructed heptane pan fire 0.5 m^2 located on the side of the mock-up (IMO-9). The extinguishment times for these tests ranged from approximately 0.5 -2.5 minutes for the spray fires located on top of the mock-up, to approximately 1-4.5 minutes for the spray fires located on the side of the mock-up. The 0.5 m^2 heptane pan fire located on the side of the mock-up (IMO-9) was never extinguished by this system. At many times during this test (IMO-9), the fire was almost extinguished but kept being reignited by the hot metal surfaces on the side of the pan. During the tests of the Reliable MistaFire System, the obstructed fires were extinguished when the oxygen concentration measured at the base of the fire dropped below 17.5 percent.

7.5.4 Securiplex

The Securiplex system is a twin-fluid system that operates at a pressure of 5.5 bar (80 psi) for both fluids. Each fluid (water and air) is supplied to the nozzle via a separate set of piping. At this operating pressure, the individual nozzles flow approximately 5.0 Lpm (1.32 gpm) of water and 0.23 m^3/min. (8.0 ft^3/min.) of air. This water flow rate corresponds to total system flow rate of 140 Lpm (37 gpm) and an application rate of 1.8 Lpm/m^2 (0.045 gpm/ft^2), the lowest application rate evaluated during these tests.

The Securiplex system produced somewhat mixed results during this evaluation. The system did well against the large unobstructed spray fires (i.e., 2.0, 6.0 MW fires) but showed mixed results against the smaller fires (i.e., 1.0 MW fires). The Securiplex system quickly extinguished (approximately 1:00 min) the two larger heptane spray fires on top of the mock-up (2.0 and 6.0 MW), but required over nine minutes to extinguish the 1.0 MW heptane spray fire on top of the mock-up. The Securiplex system also could not extinguish the small heptane pan fire located on the side of the mock-up (the 0.5 m^2 heptane pan (IMO-9)) The difficulty in extinguishing this fire appears to be related to both the oxygen concentration at the base of the fire and with the drop size characteristics of the system. The similarity in the spray characteristics between the Securiplex nozzles ($Dv_{50} \approx 200$ microns) and the Kidde Fenwal nozzles ($Dv_{50} \approx 200$ - 300 microns) suggest that the Securiplex nozzles produce adequate amounts of small drops to extinguish this fire. This is also supported by the capabilities exhibited by this system in extinguishing the remaining obstructed fires. The Securiplex system typically extinguished these obstructed fires when the oxygen concentration measured at the base of the fire dropped to approximately 18 percent. This is higher than any of the systems evaluated during these tests. This decreased dependency on oxygen depletion may be associated with better mixing produced by the use of the atomizing fluid. During the 0.5 m^2 pan fire test, the oxygen concentration measured at the base of the fire only dropped to 18.6 percent. During the test of the two systems that extinguished this fire (Kidde Fenwal and Spraying Systems), the oxygen dropped below 18 percent. This suggests that the Securiplex system either does not alter the air flow into the compartment to the same degree as the Kidde Fenwal or Spraying Systems' nozzles, or the air used as the atomizing fluid is maintaining a higher oxygen concentration in the space. The use of nitrogen or other inert gases as the atomizing fluid may have also increased the performance of the system. The extinguishment times produced by the Securiplex system ranged from 1-9 minutes for the unobstructed spray fires to approximately 5 minutes for the obstructed spray fires located on the side of the mock-up. It is interesting that the Securiplex system was the only system that produced similar extinguishment times (≈ 5:30 on average) for the obstructed fires independent of the fire size or fuel type.

7.5.5 Spraying System's Modified Cluster Nozzle (7N)

The modified Spraying Systems' nozzle is a single-fluid, high-pressure system that operates at a pressure of 70 bar (1000 psi). At this pressure, the individual nozzles flow approximately 6.2 Lpm (1.6 gpm) producing a total system flow rate of 170 Lpm (45 gpm). This flow rate corresponds to an application rate of 2.2 Lpm/m^2 (0.054 gpm/ft^2).

The modified Spraying Systems' nozzles performed very well during this test series. The system was capable of extinguishing all of the test fires within the 15-minute time period required by the amended (revised IMO-9 and separate bilge protection) IMO test protocol. The extinguishment times produced by this system ranged from approximately 1:00 for the unobstructed spray fires to 2-4 minutes for the obstructed spray fires located on the side of the mock-up. The Spraying Systems' nozzles also extinguished the 0.5 m^2 (IMO-9) heptane pan fire in just over 11 minutes. The superior performance exhibited by this system was attributed to the nozzle's ability to produce and distribute large quantities of small droplets. These smaller droplets, with the aid of the turbulence created by the fire, mixed well throughout the compartment increasing the system's capabilities against partially obstructed fires. As identified previously, the extinguishment of the obstructed fires appears to be related to the oxygen concentration at the base of the fire. During these tests, the obstructed fires were extinguished when the oxygen concentration measured at the base of the fire dropped on an average below 17.5 percent. This suggests that this system produces relatively high mist concentrations at the base but is still dependent on oxygen depletion to aid in extinguishment of the obstructed fires.

7.5.6 System Performance Summary

The five candidate water mist systems were capable of extinguishing all of the spray fire evaluated during this investigation. The spray fires located on top of the mock-up were typically extinguished within 2:30 of mist system activation (with the exception of the Securiplex system which required over 9 minutes to extinguish the 1.0 MW heptane spray fire). Variations in the system's performance/capabilities were observed during the fires conducted on the side of the mock-up (obstructed fire). During the obstructed spray fires tests, the extinguishment times ranged from just over one minute to over seven minutes depending on the system, fire size and type of fuel. The two high-pressure systems (Reliable and Spraying Systems) were capable of extinguishing these fires with an average extinguishment time of approximately three minutes. The Kidde Fenwal system, the Grinnell AquaMist and Securiplex systems all require approximately five minutes to extinguish these fires. The 0.5 m^2 heptane pan fire located on the side of the mock-up proved to be the most challenging fire and served to separate the high performance systems from the rest of the field. Only the Kidde Fenwal and Spraying System's nozzles were capable of extinguishment this fire and required over ten minutes of system activation to do so. The Reliable MistaFire and Securiplex Systems were both capable of reducing the size of this fire but were unable to extinguish this fire. The Grinnell AquaMist System was not evaluated against the 0.5 m^2 pan fire. The evaluation of the AquaMist System was completed prior to the revision of the IMO test protocol. In summary, both the Kidde Fenwal and Spraying System's nozzles would have passed the IMO test protocol with the exception of the fires located in the bilge. The IMO has recently allowed separate dedicated protection of the bilge areas.

7.6 Fire Extinguishment Difficulty (Fire Size and Fire Type Comparison)

The objective of these tests was to evaluate the ease or difficulty in extinguishing a fire as a function of fire size and location. These tests were conducted using the Spraying Systems' nozzles (T series orifices) installed at the 7.0 m elevation. All of the fires conducted during this phase of the program were conducted using heptane as the fuel.

7.6.1 <u>Spray Fire</u>

Five spray fires sizes were incorporated in this evaluation (6.0, 2.0, 1.0, 0.8 and 0.6 MW). The fires were conducted on top of the mock-up as described in IMO-1 and on the side of the mock-up as described in IMO-3.

The results of the spray fire evaluation are listed in Table 9. As determined previously and found throughout the literature, the large fires were extinguished faster than the smaller fires. The obstructed fires (fires located on the side of the mock-up) were also determined to be more difficult to extinguish than unobstructed fires. The addition of obstructions typically double the extinguishment times. The extinguishment times recorded during these tests ranged from just under one minute for the 6.0 MW spray fire on the top of the mock-up to over seven and a half minutes for the 600 kW spray fire on top of the mock-up. The 800 kW spray fire on the side of the mock-up was never extinguished. The 600 kW fire was, therefore, eliminated from the obstructed fire tests on the assumption that it would not be extinguished.

Table 9. Spray Fire Size Evaluation
(Modified Spraying Systems' Nozzles (T series orifices), 7.0 m elevation)

Fire Scenario	Extinguishment Time (min:sec)	*Oxygen Concentration (%)
6.0 MW Heptane Spray Top	0:57	17.7
2.0 MW Heptane Spray Top	1:40	18.0
1.0 MW Heptane Spray Top	1:57	18.2
0.8 MW Heptane Spray Top	5:09	18.9
0.6 MW Heptane Spray Top	7:40	18.6
6.0 MW Heptane Spray Side	1:40	17.2
2.0 MW Heptane Spray Side	3:28	16.9
1.0 MW Heptane Spray Side	5:50	16.7
0.8 MW Heptane Spray Side	NO	17.3

Notes: NO = No extinguishment during the 15-minute discharge
* = Oxygen concentration measured at the base of the fire at extinguishment

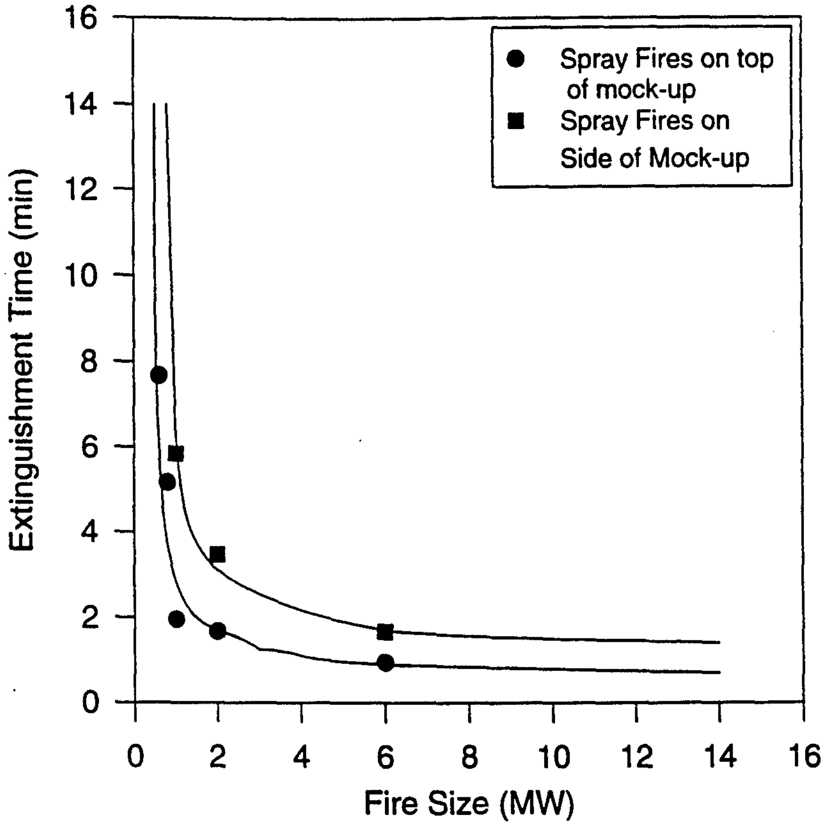
The extinguishment times are plotted versus fire size in Figure 20A. The plot identifies a critical fire size, below which extinguishment becomes extremely difficult. This critical value is not solely related to the fire size, but instead is related to the combined effects of fire size, compartment volume and compartment ventilation conditions as well as water mist characteristics. For relatively large fire size to compartment volume ratios (values need to be determined), it may be more appropriate to express this relation in terms of equivalence ratio (fire size/maximum fire size the vent can support) rather than fire size itself. This data also suggests the existence of a family of curves relating the degree of obstruction and fire size to the extinguishment time. As an example, the trends observed for fires conducted on the side of the mock-up basically represent a fire shielded by a 1.0 m (3.3 ft) horizontal obstruction. Other curves need to be developed for both smaller and larger obstructions.

The need for some degree of oxygen depletion to aid in extinguishment is illustrated in Figure 20B. As shown in this figure and Table 10, a majority of the unobstructed fires are extinguished when the oxygen concentration measured at the base of the fire drops below 18 percent. The obstructed fires were extinguished when the oxygen concentration measured at the base of the fire dropped below 17 percent. These differences in oxygen concentration needed for extinguishment are related to the amount of mist reaching the fire (mist concentration at the fire location). The obstructed fires are located in areas of lower mist concentration and require a lower oxygen concentration to achieve extinguishment. As mentioned previously, the amount of mist reaching an obstructed fire is dependent on the spray characteristics of the mist system (drop size distribution, spray momentum, and system flow rate), the nature of the obstruction, and the characteristics of the fire. This was illustrated in the results of the system comparison tests (Table 8). In general, the systems that produced and mixed small drops throughout the compartment were less dependent on oxygen depletion and produced faster extinguishment times for the obstructed fires than the systems with larger drop sizes.

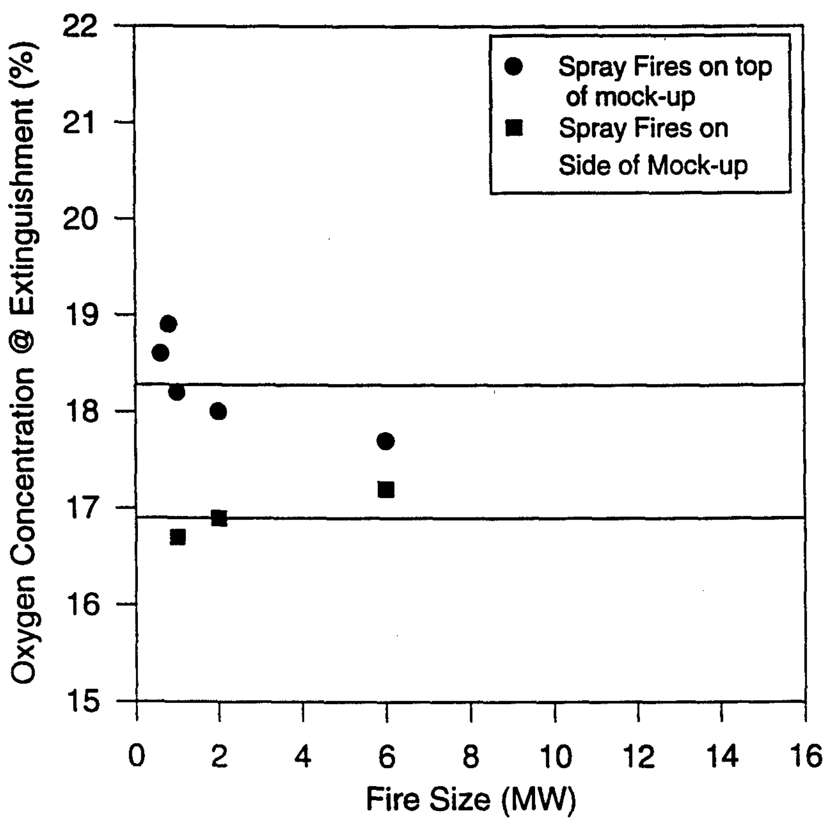
7.6.2 Pan Fires

Three pan fire sizes were used in this evaluation (1.0 m^2, 0.5 m^2 and 0.1 m^2). The heat release rates of these fires were estimated to be 3.3 MW, 1.6 MW and 0.25 MW, respectively.[6] Each pan was constructed with 15 cm (6.0 in.) sides resulting in a 10 cm (4.0 in.) free board once filled with 5 cm (2.0 in.) of heptane. The pan fires were evaluated at three locations in the space: on top of the mock-up, on the lower deck and on the bilge plating under the obstruction plate. These three locations were selected to represent two unobstructed locations presumed to be similar with respect to mist concentration but different spray momentum (velocity) and one obstructed location.

The results of the pan fire evaluation are listed in Table 10. In summary, the pan fire results follow the trends observed during the spray fire evaluation. The larger fires were extinguished faster than the smaller fires and the obstructed fires required longer to extinguish than the unobstructed fires. It should be noted that while the 0.1 m^2 pan fire was typically



(a) Extinguishment Times



(b) Oxygen Concentrations

Figure 20. Extinguishment Difficulty Spray Fire Site Evalutation

reduced to small licks of flame located in the corners of the pan, it was not completely extinguished at any of the three locations.

Table 10. Pan Fire Size Evaluation Modified Spraying Systems' Nozzles
(T series orifices, 7.0 m Elevation)

Fire Scenario	Fire Size	Extinguishment Time (min:sec)	*Oxygen Concentration (%)
0.1 m^2 Heptane Pan Top	0.13 MW	NO	20.6
0.5 m^2 Heptane Pan Top	1.2 MW	NO	18.7
1.0 m^2 Heptane Pan Top	3.1 MW	13:30	18.2
3.0 m^2 Heptane Pan Top	13.0 MW	3:30	18.2
0.1 m^2 Heptane Pan Low	0.13 MW	NO	20.2
0.5 m^2 Heptane Pan Low	1.2 MW	6:30	18.9
1.0 m^2 Heptane Pan Low	3.1 MW	1:35	18.9
0.1 m^2 Heptane Pan Side	0.13 MW	NO	20.8
0.5 m^2 Heptane Pan Side	1.2 MW	11:20	17.8
1.0 m^2 Heptane Pan Side	3.1 MW	6:15	16.6

Notes: NO = No extinguishment during the 15-minute discharge
* = Oxygen concentration measured at the base of the fire at extinguishment

The relation of extinguishment time to fire size followed the same trends identified in the spray fire evaluation with the exception of the fires located on top of the mock-up (Figure 21A and 21B). It should be noted that the shape of the plot shown in Figure 21A is assumed from the spray fire relationship and could not be developed based on the two successful tests (tests where the fire was extinguished) conducted at each location. The fires located on top of the mock-up required longer to extinguish than the fires located elsewhere in the space. The fires on top of the mock-up are intentionally located in an area of lower mist concentration (between four nozzles). This lower mist concentration results from inadequate spray pattern coverage. Shadowing effects produced by the high pan sides may also contribute to the increased difficulty of extinguishment. These high pan sides tend to shield the fires located in the corners of the pan from horizontal mist flow from at least two sides. When the pans are positioned on the lower

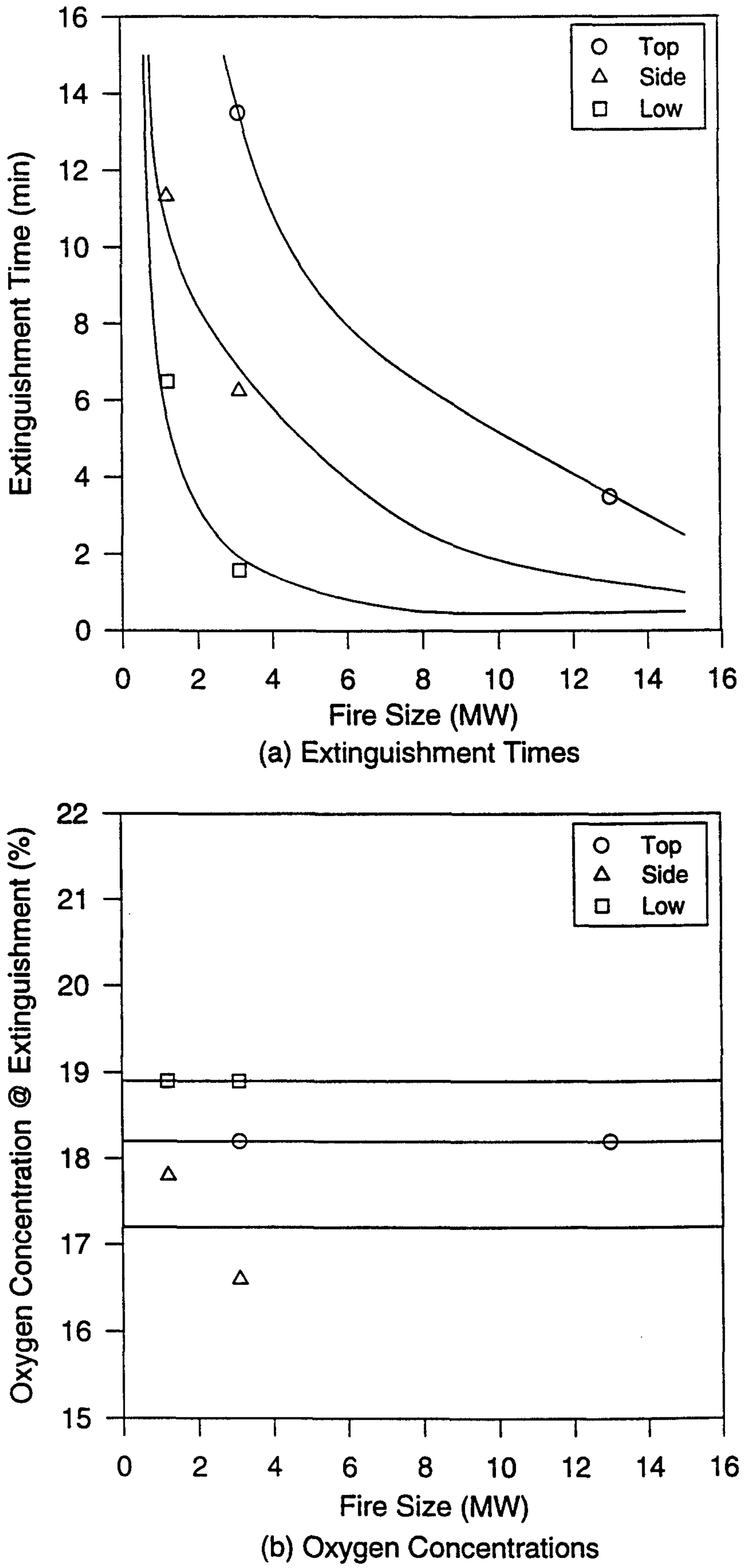


Figure 21. Extinguishment Difficulty Pan Fire Size Evaluation

deck, the majority of the mist is falling vertically from above increasing the amount of mist discharged into the corners of the pan. In summary, the difference in extinguishment characteristics between the pan fires located high in the space and those located at deck level is related to a variety of parameters, the effects of which may vary with location in the space.

As observed during the obstructed spray fire tests, the obstructed pan fires required significant oxygen depletion in order to be extinguished. A noticeable difference was observed during the extinguishment of the obstructed and unobstructed fires. During the unobstructed fire tests, upon mist system activation, the fires were instantly reduced in size and remained as small licks of flame until either the fire was completely extinguished or the test was terminated. During the obstructed fire tests, the fire appeared to burn unabated until the fire began to deplete oxygen concentration in the space. At this point, the fire separated (blow-off) from the fuel surface and was extinguished.

On a final note, the discharge of mist significantly reduces the heat release rate of the unobstructed pan fires (based on visual observations). These smaller fires are either extinguished or continue to burn indefinitely. Unfortunately, it is uncertain how to include this reduction in fire size in the relation between the extinguishment time and fire size.

7.6.3 Fire Type Comparison

The extinguishment times for all of the fires conducted on top of the mock-up are plotted versus fire size in Figure 22A. As shown in this figure, for a given fire size, pan fires are more difficult to extinguish than spray fires. There are at least two potential variables associated with this difference in extinguishment difficulty. First, the spray fires may produce better mixing in the space as a result of the turbulence created by the fuel spray jet. This increased turbulence may also aid in the entrainment of mist into the flame. Second, the spray fires have a higher strain rate than pool fires and consequently are much easier to extinguish. The high sides of the pans may also shield the fires from much of the horizontal dispersion of mist.

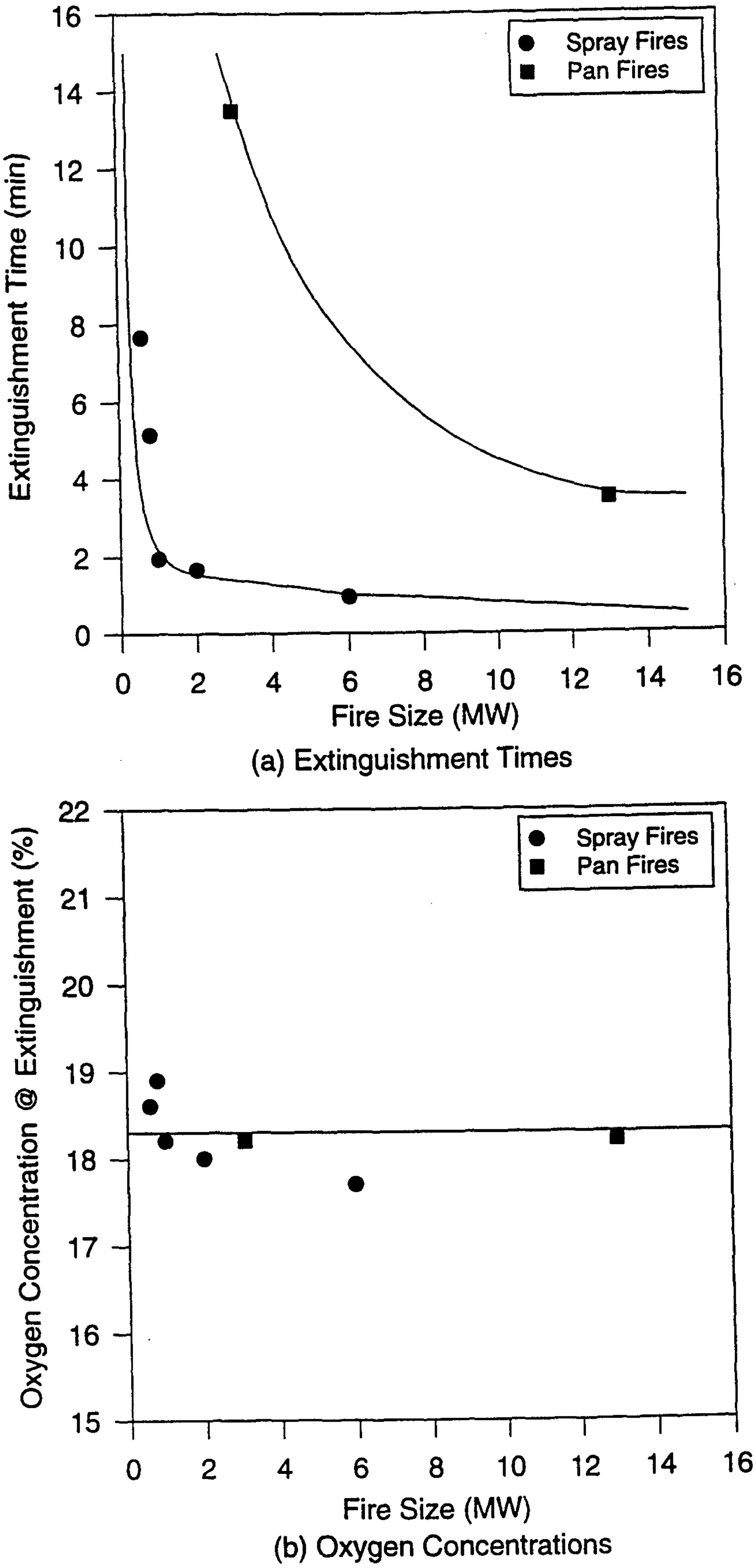


Figure 22. Extinguishment Difficulty Fire Type Evaluation

It should be noted that the previous evaluation was conducted with heptane and that the use of a higher flashpoint fuel (i.e., diesel) may have reduced the extinguishment times for both types of fires. However, the reduction in the pan fire extinguishment times would be more due to the surface cooling effects of the mist. Another interesting observation made during these tests was that the unobstructed pan fires were extinguished when the oxygen concentration measure at the base of the fire dropped between 18-19 percent (Figure 22B). The oxygen concentration at extinguishment of the spray fires appears to decrease with increased fire size.

7.7 Increased Mist Discharge Rate Tests

The objective of these tests was to determine what effect a significantly higher mist discharge rate has on the fire extinguishing capabilities of a candidate water mist system. During these tests, mist was discharged from nozzles in both the 5.0 m and 7.0 m pipe networks. The 5.0 m grid was relocated ½-nozzle spacing (0.75 m (2.5 ft)) forward to produce a staggered nozzle installation. This configuration approximately doubled the amount of mist in the space without significantly altering the drop size distribution or mist dispersion (mixing) characteristics of the system.

The results of these tests are shown in Table 11. As shown in Table 11, the increase in mist reduced the extinguishment times of the unobstructed spray fires (top) but produced mixed results against the obstructed spray fires (side). Mixed results were also observed during the pan fire evaluation. The unobstructed spray fires were extinguished significantly faster (in most cases almost twice as fast) using the higher mist discharge rate. The dependency on oxygen depletion to aid in extinguishment was also reduced. The oxygen concentration measured at extinguishment was typically about one percent higher for the multi-level system than for the original single-level system (18.7 vs. 18.0) . This was attributed to the fact that more mist was reaching the fire. The fires conducted on the side of the mock-up, however, showed only a slight decrease in extinguishment time. It is uncertain whether the slight increase in performance was a result of a higher mist concentration under the obstruction, or possibly, normal scatter in the data. The addition of nozzles other than in the overhead of the space could increase the amount of mist reaching these obstructed fires, but is beyond the scope of this investigation. Consistent with previous data, the pan fire tests produced mixed results during this phase of the investigation.

Table 11. Single v. Multiple Level System Comparison
Modified Spraying Systems' Nozzles (T series orifices)

Fire Scenario	Single Level - 2.3 Lpm/m^2 (0.054 gpm/ft^2)		Multiple Level - 4.2 Lpm/m^2 (0.10 gpm/ft^2)	
	Extinguishment Time (min:sec)	*Oxygen Concentration (%)	Extinguishment Time (min:sec)	*Oxygen Concentration (%)
6.0 MW Heptane Spray Top	0:57	17.7	0:20	18.7
2.0 MW Heptane Spray Top	1:40	18.0	0:50	18.7
0.8 MW Heptane Spray Top	5:09	18.9	4:40	18.8
6.0 MW Heptane Spray Side	1:40	17.2	1:40	17.6
2.0 MW Heptane Spray Side	3:28	16.9	2:30	17.6
0.8 MW Heptane Spray Side	NO	17.5	NO	18.9
0.5 m^2 Heptane Pan Top	NO	18.7	0:46	20.3
0.5 m^2 Heptane Pan Low	6:30	18.9	NO	18.5
0.5 m^2 Heptane Pan Side	11:20	17.8	9:47	17.7

Notes: NO = No extinguishment during the 15-minute discharge
* = Oxygen concentration measured at the base of the fire at extinguishment

7.8 Increased Mist Discharge Rate Open Roof Vent Tests

The results of the tests with the higher discharge rates and open roof vents are listed in Table 12. The tests were again conducted with 25 percent of the overhead of the space removed. As shown in Section 7.4 of this report, increased ventilation dramatically reduces the capabilities of the candidate water mist systems. During the tests conducted with the open roof vent, a significant amount of steam and mist was lost through the opening in the overhead, and the temperature in the space is unaffected by the fire. The oxygen concentration in the space was observed to deviate only slightly from ambient conditions (21%). Consequently, due to the lack of enclosure effects, even the multiple level system was only capable of extinguishing three of the five test fires (all unobstructed fires). The obstructed fires (fires located on the side of the mock-up) were not tested but it is presumed they would have been too challenging for the mist systems to extinguish in an open space.

Table 12. Increased Mist Discharge Rate Open Roof Vent Evaluation Results
Modified Spraying Systems' Nozzles (T series orifices)

Fire Scenario	IMO Vent		IMO Open Roof and Vent	
	Extinguishment Time (min:sec)	*Oxygen Concentration (%)	Extinguishment Time (min:sec)	*Oxygen Concentration (%)
6.0 MW Heptane Spray Top	0:20	18.7	2:30	19.5
2.0 MW Heptane Spray Top	0:50	18.7	14:40	19.8
0.8 MW Heptane Spray Top	4:40	18.8	NO	20.5
0.5 m^2 Heptane Pan Top	0:46	20.3	1:30	20.7
0.5 m^2 Heptane Pan Low	NO	18.5	NO	20.8

Notes: NO = No extinguishment during the 15-minute discharge
N/A = Not tested (These tests were eliminated due to the results of other tests. The results are assumed to be no extinguishment.)
* = Oxygen concentration measured at the base of the fire at extinguishment

The extinguishment times are plotted versus fire size for both the open and closed compartment in Figure 23. The lack of enclosure effects appear to shift the relation between extinguishment time to fire size toward the larger fires (to the right). As shown in Figure 23, the extinguishment times for the smaller fires were significantly influenced by the open roof vent. This suggests that the effects of mist entrainment and localized steam production are more predominant for larger fires. The oxygen concentrations measured at the base of the fire during extinguishment were observed to be approximately one percent higher for the open roof tests than measured during the tests conducted using the standard IMO test configuration (20.7 v. 19.7).

7.9 Parameters Associated With Extinguishment

The results of these tests confirm that the extinguishment of fires using water mist is strongly dependent on the characteristics of the enclosure (i.e., volume, shape, clutter and ventilation conditions). The enclosure has numerous effects on the extinguishment process. First, the enclosure confines the mist allowing the build-up of a mist concentration. Second, the enclosure confines heat, thus aiding in the production of steam. Third, the enclosure confines the products of combustion and steam thus contributing to the depletion of oxygen in the space. These effects are further described in the following sections of this report.

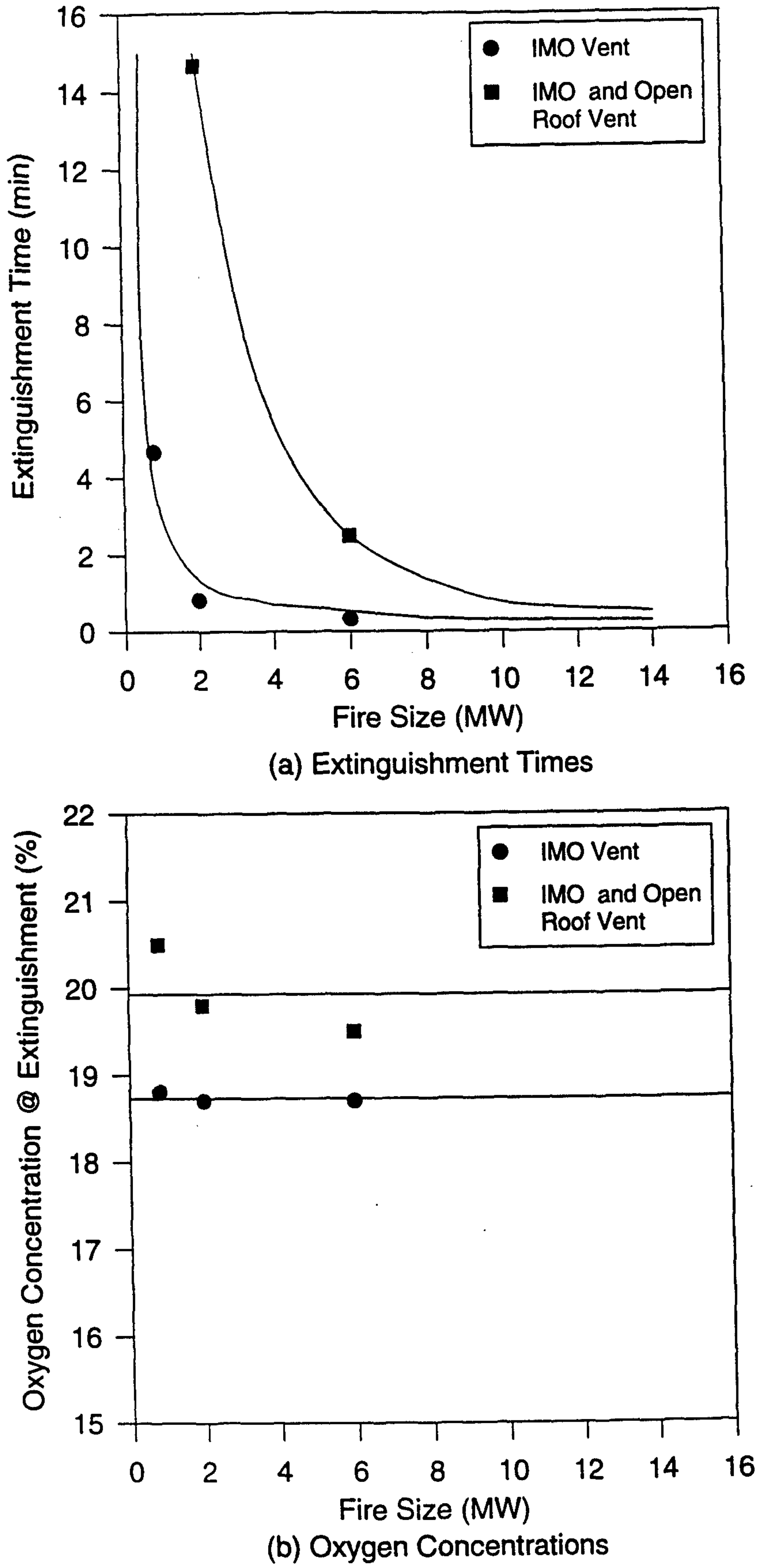


Figure 23. Increased Mist Discharge Rate Open Roof Vent Comparison

7.9.1 Oxygen Depletion Effects

Oxygen depletion has been identified as one of the contributing factors in extinguishing shielded/obstructed fires [3,7]. These tests illustrate that fires can still be extinguished in locations of lower mist concentrations with some help from oxygen depletion. The oxygen concentrations measured at the base of each fire during extinguishment were shown in Table 8 for the five systems evaluated during this test series. The fires requiring additional help from oxygen depletion were the spray fires located on the side of the mock-up (IMO-3, IMO-6, ARMY-4, and ARMY-5). The oxygen concentration measured at extinguishment of these fires were typically 2-3 percent lower than the unobstructed fires. The obstructed spray fires were extinguished when the oxygen concentration dropped between 15-17 percent depending on the characteristics of the mist system being evaluated. (Thirteen percent is the limiting oxygen index for most hydrocarbon fuels [8]). The unobstructed fires (fire located on top of the mock-up) were extinguished with oxygen concentrations anywhere between 16 to 21 percent.

The following modeling exercise was conducted to demonstrate proof of concept. Future applications of this approach will need to address the effects the mist has on the compartment temperatures and vent flow characteristics. One such approach is given in the temperature predictions section of this report (Section 7.10). During this exercise, the conditions in the compartment (temperature, oxygen concentrations and layer depth) were modeled using CFAST [9]. The input parameters to the model are found in Appendix D. The model was used to predict the oxygen concentration histories in the compartment as a function of fire size. These oxygen concentration histories were then used to predict the extinguishment times of these fires based on the average oxygen concentrations measured during extinguishment.

The oxygen concentrations measured at extinguishment during the fire size evaluation (Section 7.6) were selected for this analysis. These tests were conducted using the modified Spraying Systems' nozzles (T series orifices) installed at a 7.0 m elevation. The oxygen concentration measured at the base of the heptane spray fires during extinguishment of the fire ranged from approximately 18 percent for the unobstructed fires to 16.5 percent for the obstructed fires as shown in Figure 20. It should be noted that the oxygen concentrations required for extinguishment are a function of the amount of mist reaching the fire as well as the drop size distribution of the system. (The drop size distribution is related to the efficiency of the droplets to absorb heat from the flame.)

The oxygen concentration histories predicted by the model for three fire sizes (6.0 MW, 2.0 MW and 1.0 MW) are shown in Figure 24. The times required to reach the oxygen concentration needed to extinguish these fires were determined from this figure and plotted along with the results of the spray fire evaluation in Figure 25. As shown in Figure 25, this approach provides a fairly accurate means of predicting the extinguishment times for these fires. The results can be applied to the unobstructed fires with a high degree of confidence (due to mist uniformity), but caution should be used when applying these results to obstructed fires. The oxygen concentration required to extinguish obstructed fires is highly dependent on the degree of obstruction of the fire. Further work is needed to better understand the oxygen depletion requirement for obstructed fires as a function of both mist concentration and/or degree of obstruction.

The ability to predict the time to extinguish a fire using CFAST appears to work well for both the unobstructed and shielded spray fires evaluated during this experimental program. However, the ability to apply this approach to pan fires or class A materials is significantly more difficult. The difficulty in applying this approach to these fires is related to a reduction in fire size resulting from the discharge of the mist. It is not obvious how to address this fire size reduction using this technique.

A more appropriate application of the model would be to predict the oxygen concentration in the space prior to mist system activation and could be used to evaluate the effect that built-in time delays would have on the overall performance of the system.

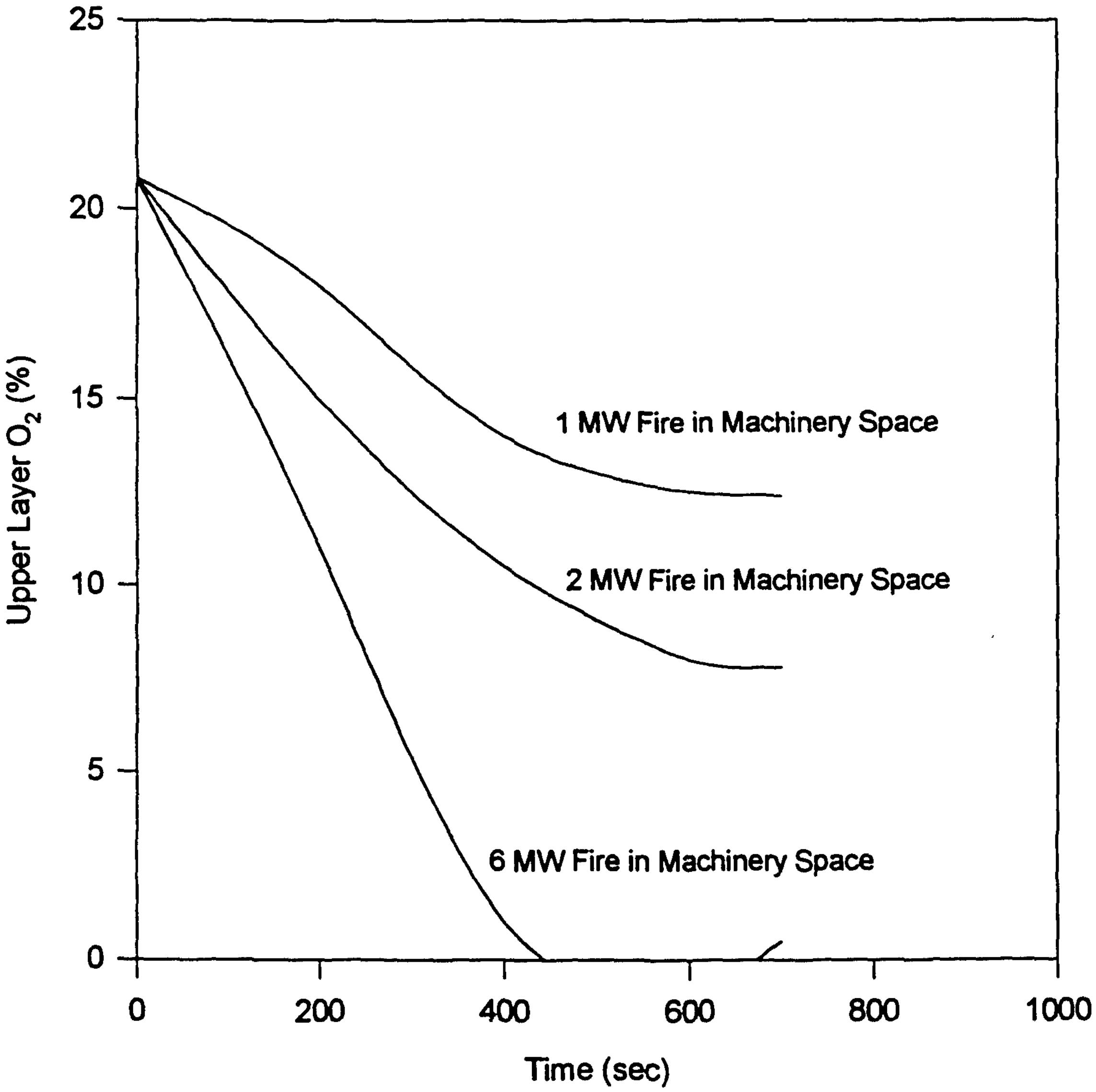


Figure 24. - Oxygen Concentrations Predicted using CFAST

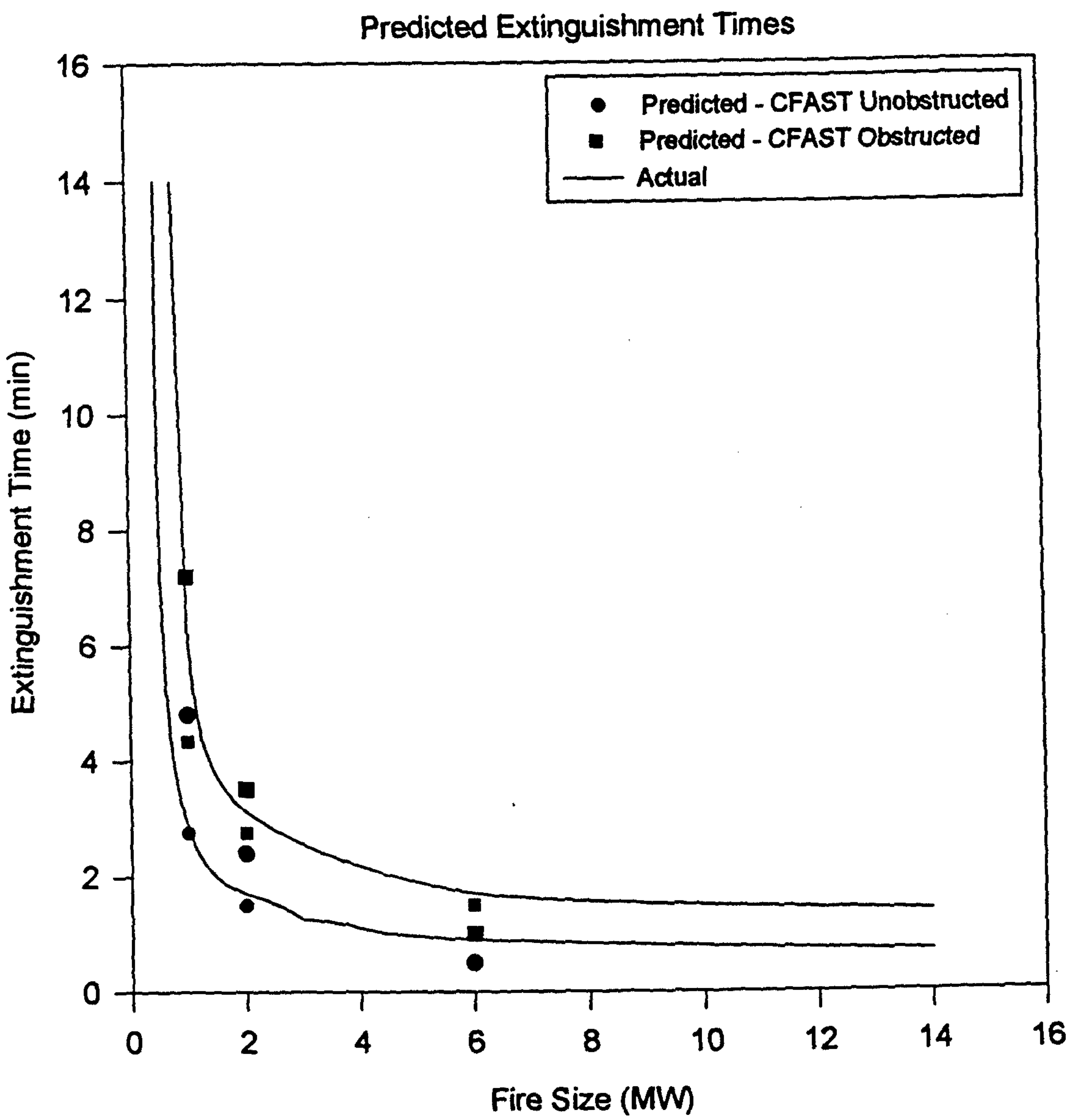


Figure 25. Predicted Extinguishment Times

7.9.2 Steam Production

Steam production and condensation of the steam back into small droplets may also be a contributing factor in the extinguishment process. The production of steam can aid in extinguishment in many ways. First, steam reduces the oxygen concentration due to dilution effects. This dilution can occur on both a localized or global scale. Secondly, as the steam cools, it condenses back into mist (very small droplets), effectively changing the drop size characteristics in the space. The gaseous behavior of the steam and the small droplets being condensed out of the steam increases the mist system's capabilities against obstructed fires.

The dilution of oxygen by steam and/or saturated vapor is difficult to measure using conventional oxygen analyzers. The sample would need to be maintained at constant temperature and pressure as it is drawn from the space and passed through the analyzer. In addition, the water droplets in the sample would need to be removed prior to the measurement of the sample.

An interesting approach to evaluating the effects of steam and/or water vapor (saturated) on extinguishment can be conducted based on the information provided in the saturated steam tables [10]. If we assume that when mist is discharged into a space (independent of the system), the air in the space becomes saturated with water vapor and this vapor reaches equilibrium quickly, using the temperatures measured in the space, we can calculate the oxygen available for combustion by applying Dalton's law of partial pressures. One such analysis is shown in Figure 26. Assuming that the limiting oxygen index for most hydrocarbon fuels using water mist/water vapor as the diluent is approximately 13-14 percent [8], Figure 26 illustrates that the uniform temperature of the space can never exceed 75°C without the fire being extinguished by steam smothering alone. This is in agreement with the temperatures measured during this test program. In general, the temperature measurements were uniform throughout the compartment during mist discharge and were observed to range from 50-70°C (122 -158° F) depending on the fire scenario, mist system and extinguishment time. The oxygen dilution effects become more significant with increases of temperatures in this range.

Also shown in Figure 26 are data associated with human tenability for hot dry air and saturated steam. As shown in this figure, the space becomes untenable for both humans and the fire at roughly the same temperature. While this information does not provide any insight for designing water mist systems or understanding how water mist extinguishes a fire, it does suggest that if the water mist system is activated, it is unlikely that untenable thermal conditions can occur in the space. (This statement assumes uniform conditions throughout the compartment and does not consider areas in close proximity to the fire.)

An amount of recondensed steam being produced during the extinguishment of a large fire can be seen by comparing the optimal density measurements (ODM) recorded during two tests conducted with the Grinnell AquaMist nozzles (a cold discharge test (no fire) and a 2.0 MW heptane spray fire located on top of the mock-up). This comparison is shown in Figure 27. As shown in Figure 27, during the cold discharge test, the mist concentration reduces transmittance of the ODMs on the order of 10-40 percent. The obscuration range is related to a gradient in the mist concentration with the highest concentration located low in the space (greatest reduction in transmittance) and decreases with elevation (lowers reduction in transmittance). During the 2.0 MW heptane spray fire, the reduction of transmittance was more uniform and was observed to be on the order of 80 percent. This was primarily the result of steam production and condensation. The products of combustion (primarily soot) produced by the heptane spray fire itself tend to reduce the optical density at the 6.0 m (19.7 ft) elevation by 10 percent but usually have little or no effect on the ODM's at the 4.0 m (13.0 ft) and 2.0 m (6.5 ft) levels. Also note in Figure 27 that during the fire test, the concentration gradient was reversed with higher concentrations observed at the higher elevations in the space. The reversal of the concentration gradient is related to both the in-flow of cool air low in the space and the heating steam rising and condensing.

The oxygen concentrations measured at the base of the fires during extinguishment have been adjusted based on the temperatures in the space and the assumption of saturated vapor. The adjusted concentrations are listed in Table 13. As shown in Table 13, the adjustment appears to affect all five systems equally, reducing the measured concentration by one or two percentage points. The adjusted oxygen concentrations for the obstructed fires were still typically 2-3

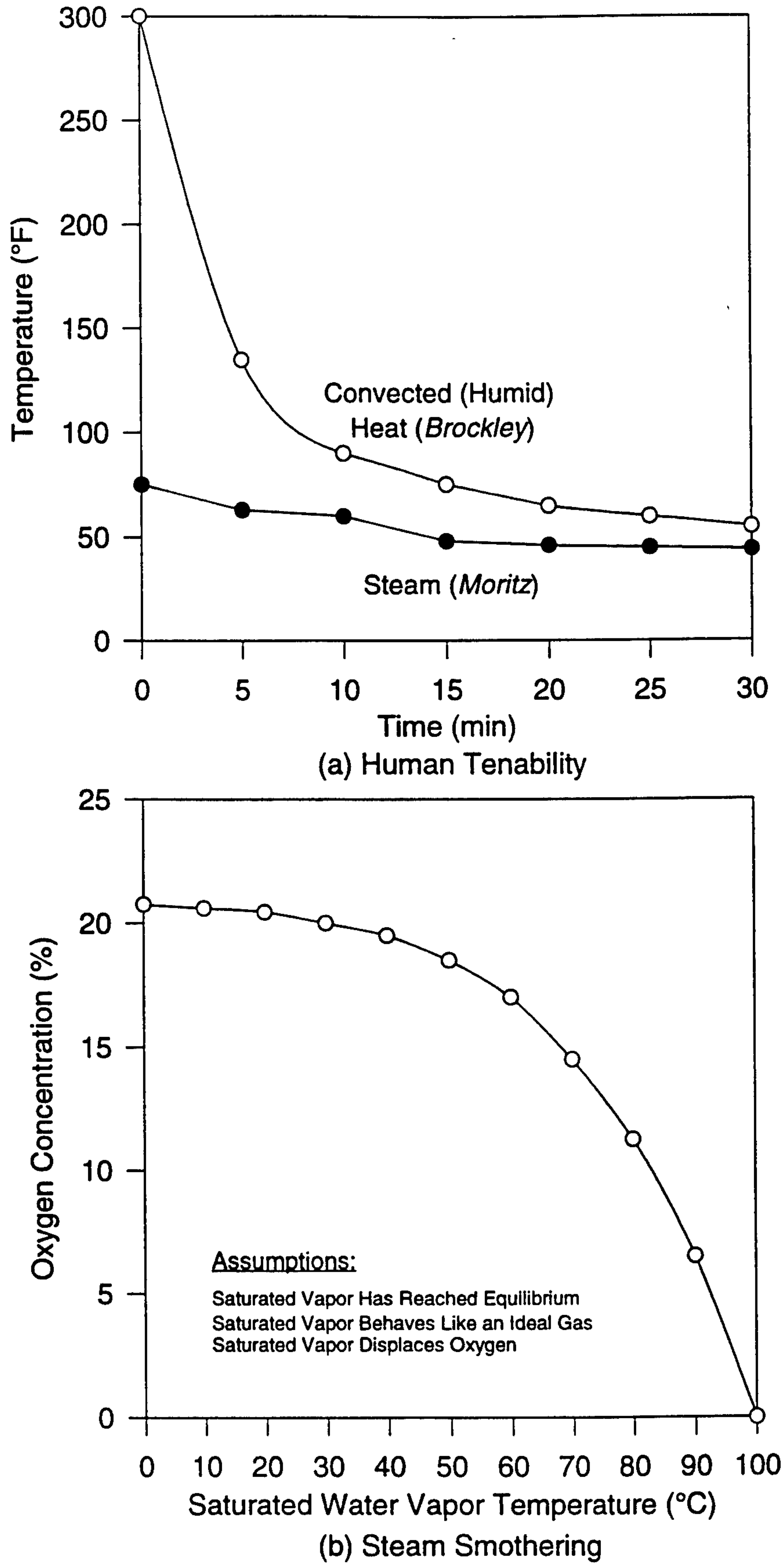
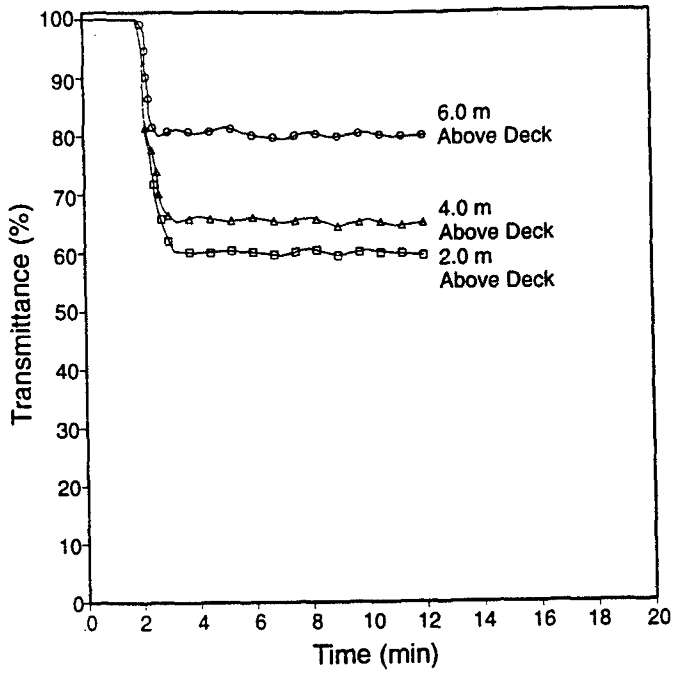
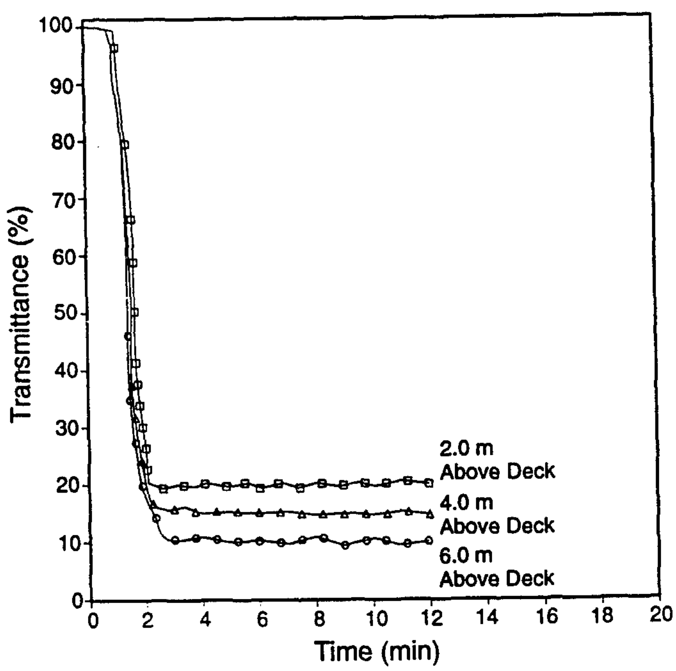


Figure 26. Oxygen Displacement Resulting from Saturated Water Vapor



(a) Grinnell Aquamist System (No Fire)



(b) Grinnell Aquamist System with 2.0 MW Fire

Figure 27. Optical Density Comparison (Steam Production and Condensation)

Table 13. Oxygen Concentrations during Extinguishment

Fire Scenario	Extinguishment Times (min:sec) Oxygen Concentration (%) ( ) = measured [ ] = corrected				
	Grinnell AquaMist 340 Lpm; 12 bar; 4.4 Lpm/m^2	Kidde-Fenwal 315 Lpm; 12 bar 4.1 Lpm/m^2	Reliable 254 Lpm; 70 bar 3.3 Lpm/m^2	Securiplex 140 Lpm; 5.5 bar 1.8 Lpm/m^2	Spraying Systems 170 Lpm; 70 bar 2.2 Lpm/m^2
1.0 MW Heptane spray fire on top of simulated engine	2:17 (19.2) [18.4]	1:34 (18.5) [18.0]	N/A	9:16 (18.1) [17.4]	1:38 (18.8) [17.6]
1.0 MW Heptane spray fire on top of reignition source of simulated engine	0:20 (19.5) [0.0]	--	0:30 (17.0) [0.0]	--	0:26 (18.5) [0.0]
2.0 MW Heptane spray fire on top of simulated engine	1:18 (17.8) [15.0]	0:50 (18.4) [17.0]	1:36 (18.3) [16.7]	1:10 (18.2) [17.4]	1:05 (18.8) [17.0]
2.0 MW Diesel spray fire on top of simulated engine	0:48 (18.8) [17.6]	0:38 (19.4) [18.4]	1:07 (19.5) [18.0]	1:15 (18.9) [17.6]	0:45 (19.3) [18.0]
6.0 MW Heptane spray fire on top of simulated engine	0:45 (17.8) [14.8]	0:44 (18.1) [16.1]	0:45 (19.5) [18.3]	0:50 (17.8) [17.1]	0:26 (18.0) [16.9]
6.0 MW Diesel spray fire on top of simulated engine	1:06 (19.3) [15.6]	1:05 (20.0) [19.2]	2:30 (19.5) [18.5]	2:30 (19.0) [17.4]	0:50 (19.5) [18.8]
3 m^2 (10.0 MW) Heptane pan fire on top of simulated engine	NO (17.0) [14.3]	6:30* (17.7) [16.9]	0:45* (19.5) [18.0]	0:50* (18.5) [17.3]	6:35 (18.5) [16.8]
Heptane flowing fuel fire from top of mock-up	N/A	N/A	N/A	N/A	N/A
1.0 MW Heptane spray fire on side of simulated engine	6:30 (15.0) [12.7]	7:20 (16.9) [14.3]	3:38 (17.5) [15.4]	5:43 (18.2) [15.8]	3:44 (17.4) [14.5]
1.0 MW Diesel spray fire on side of simulated engine	5:25 (15.5) [13.2]	4:22 (17.0) [14.7]	4:25 (17.5) [15.2]	5:00 (18.3) [17.2]	3:13 (17.3) [14.4]
6.0 MW Heptane spray fire on side of simulated engine	4:45 (15.0) [13.0]	5:00 (17.5) [15.1]	1:15 (17.0) [15.3]	5:10 (16.9) [14.7]	2:03 (17.8) [15.3]
6.0 MW Diesel spray fire on side of simulated engine	5:08 (15.5) [12.8]	2:49 (17.5) [15.5]	3:45 (17.8) [15.8]	5:30 (18.0) [16.8]	3:06 (18.0) [14.9]
0.1 m^2 Heptane on top of bilge plate centered under exhaust plate	NO (21.0)	--	--	--	NO (21.0)
0.5 m^2 (1.6 MW) Heptane pan	--	12:42** (17.25) [15.3]	NO** (19.0) [17.0]	NO** (18.6) [16.8]	11:20 (17.8) [15.9]
0.5 m^2 (1.6 MW) Heptane central under mock-up	NO	N/A	N/A	N/A'	N/A
0.5 m^2 (1.6 MW) Oil central under mock-up	NO	N/A	N/A	N/A	NO

Notes: NO = No extinguishment during the 15-minute discharge
N/A = Not tested (These tests were eliminated due to the results of other tests. The results are assumed to be no extinguishment.
-- = Not tested
* = Oxygen concentration measured at the base of the fire at extinguishment
** = Large pan (0.5 m^2)

percent lower than the open/unobstructed fires. While the adjusted oxygen concentrations were consistent for a given system, the variation between systems is dramatic and appears to be a characteristic of the system.

The difference in measured and adjusted oxygen concentration is a function of the cooling efficiency of the spray (i.e., drop size, velocity, evaporation rate, etc.) as well as the mass flow rate of the system. A thorough analysis of these parameters is beyond the scope of this report.

7.9.3 Combined Fire Effects

The overall effect the fire has on the extinguishment process (i.e., oxygen depletion, steam production, and better mixing due to increasing turbulence) is best illustrated by evaluating the mist system's capabilities against the small telltale fires. The number or percent of telltale fires extinguished during a given test has been identified to be a function of the total heat release rate of the fire scenario. As shown in Figure 28, on an average, the five mist systems were capable of only extinguishing 50 percent of the telltale fires during the cold discharge tests (telltale fires only). As the overall fire size was increased, the number of telltale fires extinguished increased. During the tests conducted with the large fires (6.0 MW or larger), all of the telltales were extinguished independent of the extinguishment status of the large primary fire.

7.9.4 Carbon Monoxide Production During Extinguishment

The amount of carbon monoxide (CO) produced during the extinguishment of these fires was also analyzed. The amount of CO produced was analyzed as a function of the heat release rate of the fire. This was accomplished by plotting the ratio of CO to CO_2 produced by the fire as a function of time. Two pan fires and two spray fires (one obstructed and one unobstructed) were selected for this evaluation. The two pan fires have equivalence ratios of 0.35 and the two spray fires have equivalence ratios of 0.70. The obstructed fires appear to be extinguished by oxygen depletion while the unobstructed fires appear to be extinguished by the cooling effects of the mist (gas phase cooling). The results of this analysis are shown in Figure 29.

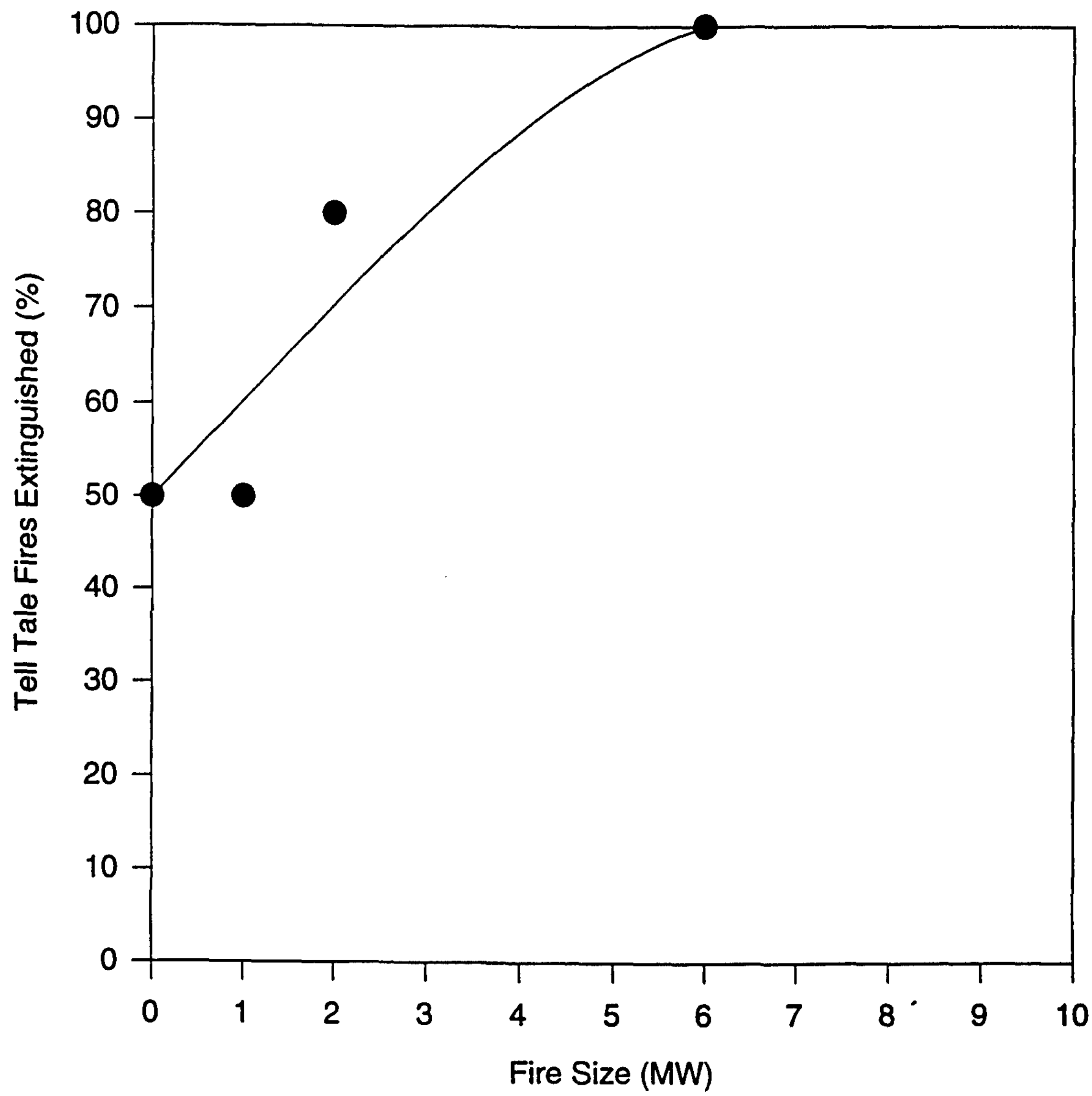


Figure 28. Telltale Extinguishment as a Function of Primary Fire Size

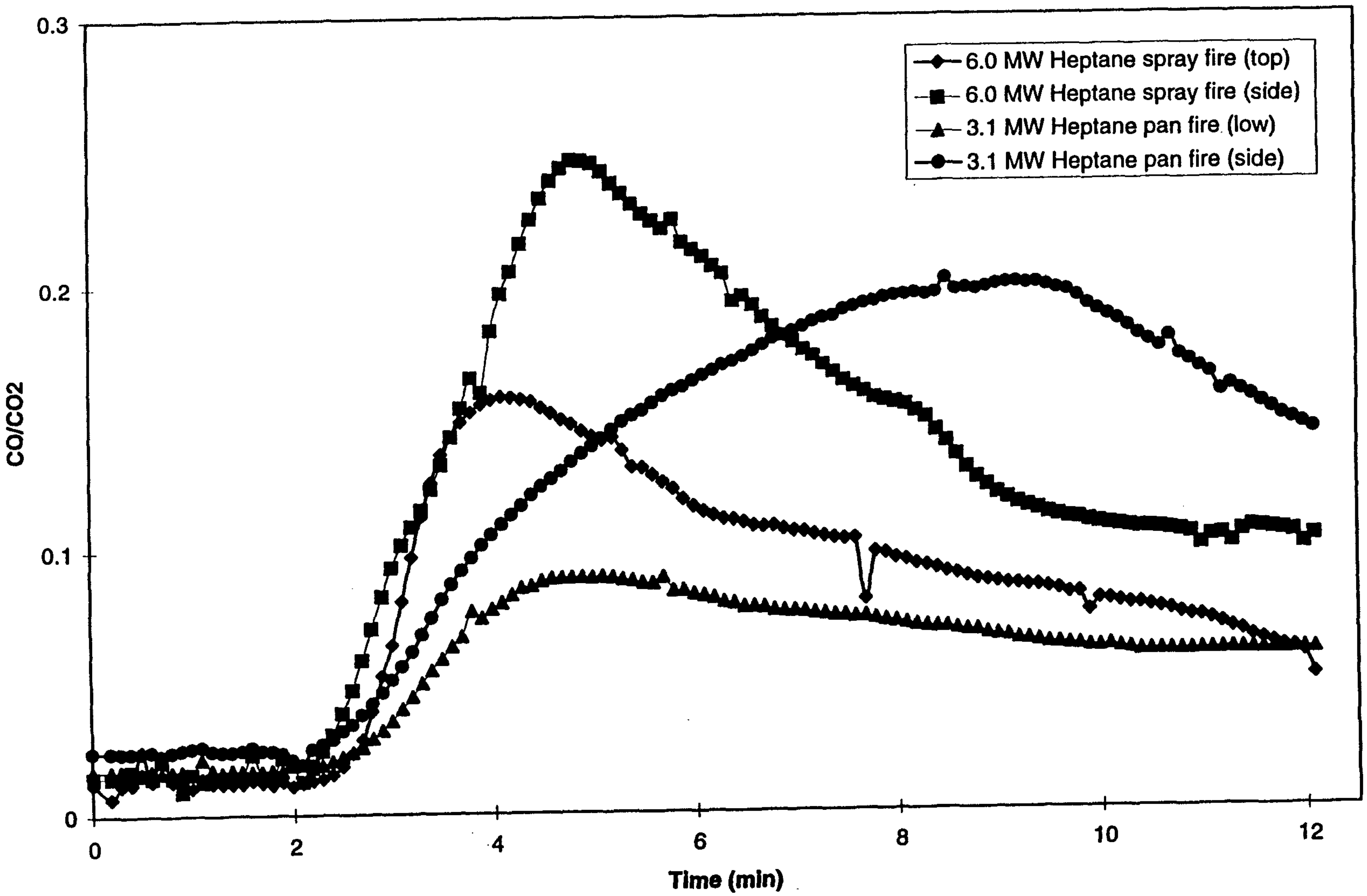


Figure 29 - Carbon monoxide production

As shown in Figure 29, the ratio of CO/CO_2 produced during the preburn is in agreement with previous studies [11] and remained well below a ratio of 0.1. The ratio of CO/CO_2 produced should remain fairly constant until the fire becomes oxygen deficient. During the extinguishment process, the CO/CO_2 ratio was observed to dramatically increase. The increased CO production was more predominant for the obstructed fires which are believed to be extinguished primarily by oxygen depletion. This is illustrated by the top two lines in Figure 29. The extinguishment of the unobstructed fires also resulted in an increased production of CO, but to a lesser degree. The amount of CO produced during extinguishment ranged from trace amounts to as high as two-tenths of a percent (2000 ppm). While the extinguishment of these fires produced significantly higher CO concentrations, the magnitude of CO produced is not life threatening for acute/short term exposures.

7.10 Compartment Temperature Predictions

During the tests conducted against the smaller fires (2.0 MW or less), the compartment appeared to reach an equilibrium condition (constant temperature) shortly after mist system activation. This equilibrium condition was more predominant during the obstructed fire tests. The unobstructed fires were typically reduced in size or extinguished in many cases before equilibrium could be reached. The fact that the larger fires were quickly extinguished may suggest that the equilibrium conditions produced by these large fires will not support the combustion process. Consequently, being able to predict when these conditions will occur can serve as an upper limit for predicting extinguishment times.

The prediction is based on an energy balance in the fire compartment. This energy balance is expressed by equation (1).

$$\dot{Q}_{Fire} = \dot{Q}_{Boundary} + \dot{Q}_{Vent} + \dot{Q}_{Water} \qquad (1)$$

where $\dot{Q}_{Fire}$ = Heat release rate of the fire

$\dot{Q}_{Boundary}$ = Heat lost through the walls, ceiling and floor

$\dot{Q}_{Vent}$ = Heat lost out of the vent opening

$\dot{Q}_{Water}$ = Heat absorbed by the mist

The following assumptions are made to simplify the calculation:

(i) combustion is complete and takes place entirely within the confines of the compartment (the heat release rate is a constant);

(ii) the temperature is uniform within the compartment at all times (after discharge);

(iii) a single surface heat transfer coefficient may be used for the entire inner surface of the compartment; and

(iv) the heat transfer through the compartment boundaries is uni-dimensional, i.e., corners and edges are ignored and the boundaries are assumed to be 'infinite slabs'.

The individual components of equation (1) are calculated as follows:

The heat release rate of the fire is calculated using the following equation:

$$\dot{Q}_{Fire} = \dot{m}_{fuel}\ \Delta Hc_{fuel} \tag{2}$$

where $\dot{m}_{Fuel}$ is the fuel consumption rate and ΔH_c is the heat of combustion of the fuel. (This equation is valid only for well ventilated fires.)

The heat lost through the boundaries of the compartment for preflashover fires can be estimated using the following equation [12]:

$$\dot{Q}_{Boundary} = h_T A\ \Delta T \tag{3}$$

where h_T is an overall heat transfer coefficient (30 W/m^2K) and A is the area of the walls and ceiling of the compartment (m^2).

The energy lost out of the vent opening is comprised of two components: the energy required to heat the air to the compartment temperature and the energy associated with the saturated water vapor leaving the compartment. The radiative losses out of the vent opening are assumed to be negligible.

The losses associated with heating the air to the compartment temperature are given by the following equation:

$$\dot{Q}_{gas} = \dot{m}_{gas} C_p \, \Delta T \tag{4}$$

where $\dot{m}_{gas}$ is the mass flow rate of fire gases out of the compartment and C_p is the specific heat of the gas. If we assume $\dot{m}_{air} \approx \dot{m}_{gas}$ (i.e., ignore the increase in mass flow rate resulting from the fuel and water), then the mass flow rate can be estimated using the following equation [13]:

$$\dot{m}_{air} = \frac{2}{3} A_v H^{1/2} C_d \rho_0 (2g)^{1/2} \left(\frac{(\rho_0 - \rho_F)/\rho_0}{[1 + (\rho_0/\rho_F)^{1/3}]^3} \right)^{1/2} \tag{5}$$

where A_v is the area of the vent opening, H is the height of the vent opening $C_d = 0.7$ and $g = 9.81$ m/s^2. The density of the gases are a function of temperature and must be calculated simultaneously with the compartment temperature. If we assume the air entering the compartment is dry and leaves as saturated vapor, the losses associated with this vapor can be determined by the following equation:

$$\dot{Q}_{H_2O\ vapor} = \dot{m}_{air} \, \gamma_{H_2O\ vapor} \, L_v \tag{6}$$

where $\dot{m}_{air}$ is calculated using equation 5, L_v is the heat of vaporization of water and $\gamma_{H2O\ vapor}$ is the mass fraction of water vapor in the gases leaving the compartment. The mass fraction can be calculated using Dawton's Law if we know the partial pressure of the water vapor. The partial pressure of the water vapor which is given by the following equation [10]:

$$Log_N\,(P_v) \;=\; 18.3 - \left(\frac{3816.44}{(T-46.13)}\right) \tag{7}$$

Notice that the heat loss associated with the water vapor does not include the heat required to heat the water to the estimated temperature. This is covered in the term associated with the water losses.

The heat absorbed by the water mist is determined by the following equation:

$$\dot{Q}_{water} = \dot{m}_{water} C_p\ \Delta T \tag{8}$$

where $\dot{m}_{water}$ is the mass flow rate of the water mist system (multilevel modified Spraying Systems nozzles, 5.36 kg/s (11.8 lb/s)) and C_p is the specific heat of water.

If the fire size, the compartment parameters and water flow rate are known, the above equations can be used to predict the temperature in the space. The predicted temperatures for a wide range of fire sizes are shown in Figure 30. Also shown in Figure 30 are the steady-state temperatures measured during the tests conducted using the modified Spraying Systems' nozzles for the small fires (<2.0 MW) located on the side of the mockup. These small fires reached steady-state conditions prior to extinguishment. The larger fires were not included in this evaluation because these fires were extinguished before steady-state conditions/temperatures were reached. As shown in Figure 30, the predicted temperatures are in agreement with the temperatures recorded during these tests.

Taking the process a step farther, we can use the predicted temperatures to calculate the oxygen concentration in the space. The calculation is based on the fire size, vent flow rate, and the assumption that the oxygen in the space is diluted by saturated water vapor. These steady-state oxygen concentrations are shown in Figure 31. If we assume that the limiting oxygen index (LOI) for most hydrocarbon fuels using water vapor as the diluent is between 13-15 percent, Figure 31 suggests that the critical fire size for this compartment, vent configuration, and water

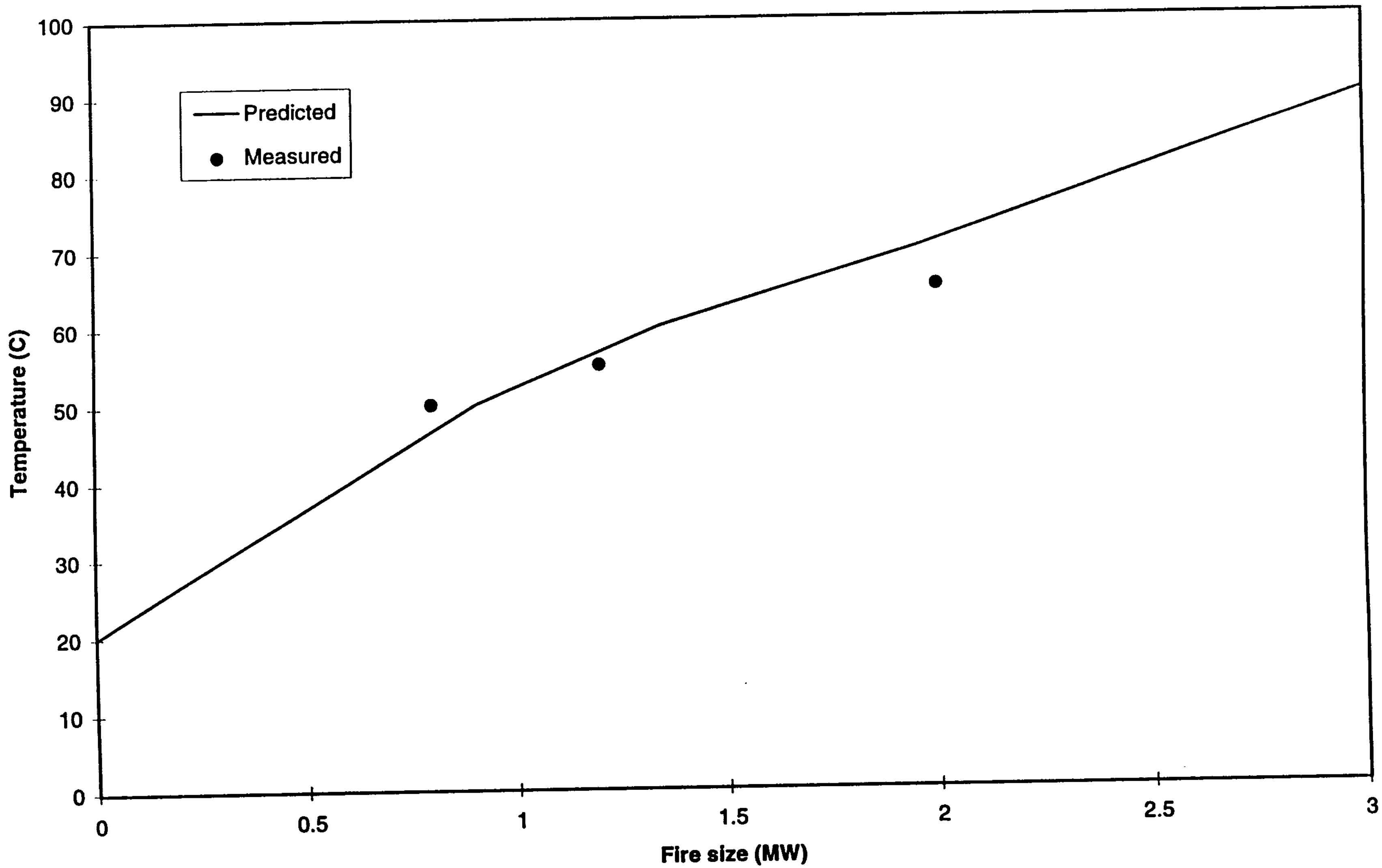


Figure 30 - Predicted steady state compartment temperatures

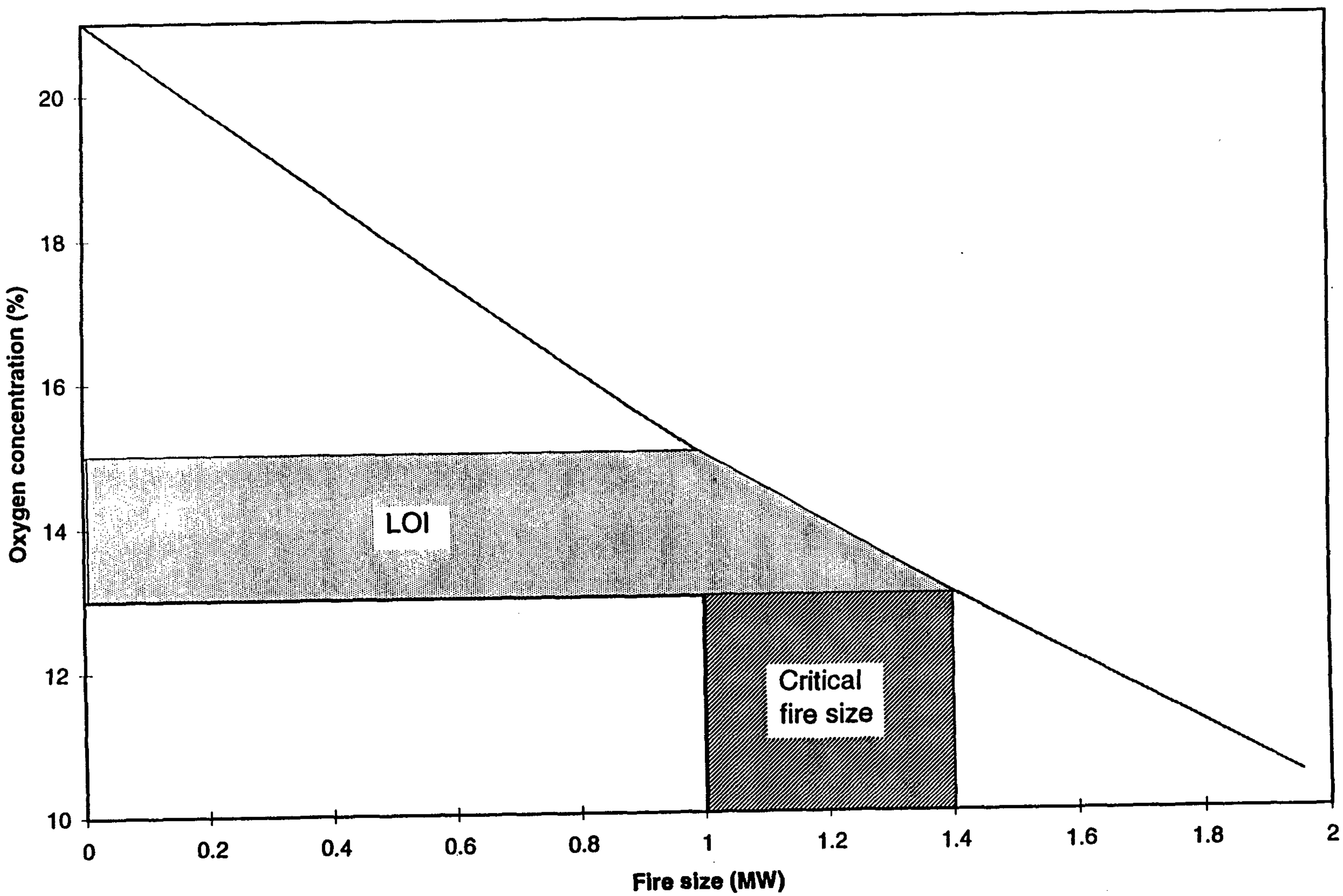


Figure 31 - Predicted steady state compartment oxygen concentrations

flow rate is between 1.0 MW and 1.4 MW. In this context, the critical fire size is defined as the size of the fire above which will produce conditions that will not support combustion due to dilution of oxygen by saturated vapor and below which does not produce adequate water vapor to sufficiently dilute the oxygen and must be extinguished by other mechanisms. The two primary assumptions used in this prediction are that (1) the fire size remains a constant until extinguishment and (2) the gases in the compartment are saturated with water vapor. Further research is needed to determine under what conditions the fire size remains constant during the extinguishment process and that the gases in the space are saturated with water vapor.

8.0 SUMMARY AND CONCLUSIONS

The fire extinguishment capabilities of water mist systems observed during this test series can be described in terms of general trends. These trends include the following:

(1) Water mist systems require minutes to extinguish fires as opposed to fractions of minutes for the gaseous halon alternatives. (These times can potentially be reduced by designing the system around the space being protected and by securing the ventilation (forced and natural) to the space prior to system activation.);

(2) Immediately after activation, water mist systems dramatically reduce the temperatures in the space, which will aid in manual intervention, minimize thermal damage, and prevent fire spread from the compartment of origin;

(3) Larger fires are easier to extinguish (with extinguishment occurring much faster) than smaller fires. (This is related to the consumption of oxygen by the fire, the generation of steam and turbulence created by the fire.);

(4) For well ventilated spray and pool fires, lower flash point fuels are more difficult to extinguish than higher flash point fuels. (This is attributed to the lack of fuel surface cooling effects and the reflash (reignition) potential of the lower flashpoint fuels.);

(5) Obstructed fires are more difficult to extinguish than unobstructed fires. This is attributed to the amount of mist actually reaching the fire (obstructions usually result in areas of lower mist concentration and, for this reason, require additional oxygen depletion to aid extinguishment);

(6) In many cases, water mist systems are incapable of extinguishing small obstructed fires. Smaller fires in the presence of larger fires are much easier to extinguish than smaller fires alone;

(7) The systems that produced small drops with high momentum demonstrated superior fire extinguishing capabilities during this evaluation (primarily due to superior capabilities against obstructed Class B fires);

(8) Larger vent openings result in high vent losses which dramatically reduce the fire fighting capabilities of the candidate water mist systems. (This is related to high mist losses, a lack of oxygen depletion and a decrease in steam production.);

(9) Increased mist discharge rates can increase the fire extinguishment capabilities of a water mist system. This increase in performance was observed primarily against unobstructed fires by reducing the time required to extinguish the fire and on the system's dependency on oxygen depletion to aid in extinguishment;

(10) During the tests included in this investigation, increasing mist discharge rates had little, if any, effect on the system's fire extinguishment capabilities against obstructed fires. Better mist dispersion through the strategic positioning of nozzles does, however, have the potential to increase the system's performance;

(11) Pan fires are more difficult to extinguish than spray fires of the same size (heat release rate). (This is related to the difference in strain rates of these fires, shielding effects produced by the sides of the pans, and the quick knock down of these fires which prevent a reduction in oxygen concentration.);

(12A) There appears to be a relation between the time required to extinguish a spray fire and the size of the fire. This relation is a function of the time required to reduce the oxygen concentration in the space below a critical value. For a given fire scenario, this critical oxygen concentration appears to be a characteristic of the water mist system and dependent on the spray characteristics of the system; and

(12B) For a known set of fire compartment, ventilation and water mist system parameters, the resulting steady-state oxygen concentrations can be estimated using an energy balance correlation. The results of this correlation can be used to identify the critical fire size for the compartment (independent of the water mist system).

In summary, these tests have demonstrated the effectiveness of using water mist technologies as a halon alternative in Category A, Class 1 (less than 500 m^3 volumes) machinery space applications. The data also indicate the ability to extrapolate the results of the IMO test protocol to spaces with similar volumes but varying ceiling heights and aspect ratios (lengths and widths). Also determined during these tests is the inability or lack of confidence in extrapolating the results of the less than 500 m^3 test protocol to significantly larger volumes. Due to the required contributions of both mist concentration and oxygen depletion to achieve extinguishment, it may be presumed that the results of a given set of tests can be extrapolated to marginally larger volumes, but the limits of this extrapolation need to be identified. Computer or mathematical models can be used to predict the amount of oxygen depletion that can be expected during the fire. If the oxygen concentration predicted by the model is significantly less than that required by the system to extinguish a fire or is less than the LOI of the fuel, one should be able to predict, with a fair degree of confidence, the performance of the system. This approach does, however, need to be validated against a wide range of fire types and a wide range of obstructions. The oxygen depletion required to extinguish the obstructed fires also suggest that it is unlikely that any of the current technologies can meet the greater than 500 m^3 test protocol as it is currently written. In order to properly evaluate water mist systems for larger spaces, the system will need to be evaluated in a space of roughly the same size (volume). This will undoubtedly be costly, but until there is better understanding of mist dispersion, flame interaction and the parameters associated with extrapolation/scaling-up to larger spaces, there appears to be no other alternative.

9.0 RECOMMENDATIONS

While the IMO test protocol provides valuable information related to the fire extinguishing capabilities of a water mist system in machinery spaces with similar characteristics (i.e., volume and ventilation conditions), the tests provide minimal information on the limits of each system and on how variations in compartment conditions would affect the overall performance of the system.

The limits of each system with respect to fire obstructions and shielding need to be identified. A family of curves, relating the required oxygen concentration needed for extinguishment to the degree of fire obstruction, needs to be developed for each system. The above family of curves needs to address the potential range of fire types as well as the potential range of compartment parameters. These parameters include fire sizes to compartment volume ratio, ventilation parameters (both forced and natural) and parameters relating the two (equivalence ratios). The range of fire types also needs to be further evaluated. A better understanding of the extinguishment of pool fires and Class A materials is needed. This data combined with some predictive fire modeling could be used to predict fire performance (extinguishment times) and to identify areas in the space requiring additional nozzles other than in the overhead of the space.

Further information is required on the complex interactions of water mist in the compartment and water mist in the flame before a fundamental design philosophy can be developed.

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Appendix A

IMO Test Protocol

INTERIM TEST METHOD FOR FIRE TESTING EQUIVALENT WATER-BASED FIRE-EXTINGUISHING SYSTEMS FOR MACHINERY SPACES OF CATEGORY A AND CARGO PUMP-ROOMS

1 SCOPE

This test method is intended for evaluating the extinguishing effectiveness of water-based total flooding protect the volume fire-extinguishing systems for engine-room of category A and cargo pump-rooms. In order to define the different engine-room and possible fire scenarios the engine types are divided into different classes according to table 1.

The test method covers the minimum fire-extinguishing requirement and prevention against reignition for fires in engine-rooms.

It was developed for systems using ceiling mounted nozzles. In the tests, the use of additional nozzles to protect specific hazards by direct application is not permitted. However if referenced in the manufacturer's design and installation instructions, additional nozzles may be installed along the perimeter of the compartment to screen openings.

Table 1 - Classification of Category A engine-room

Class	Typical engine facts	Typical net volume	Typical oil flow and pressure in fuel and lubrication system
1	Auxiliary engine-room, small main machinery or purifier room, etc.	500 m³	Fuel: Low pressure 0.15-0.20 kg/s 3-6 bar High pressure 0.02 kg/s 200-300 bar Lubrication oil: 3-5 bar Hydraulic oil: 150 bar
2	Main diesel machinery in medium-sized ships such as ferries	3,000 m³	Fuel: Low pressure 0.4-0.6 kg/s at 3-8 bar High pressure 0.030 kg/s at 250 bar Lubrication oil: 3-5 bar Hydraulic oil: 150 bar
3	Main diesel machinery in large ships such as oil tankers and container ships	>3,000 m³	Fuel: Low pressure 0.7-1.0 kg/s at 3-8 bar High pressure 0.20 kg/s Lubrication oil: 3-5 bar Hydraulic oil: 150 bar

2 FIELD OF APPLICATION

The test method is applicable for water-based fire-extinguishing systems which will be used as alternative fire-extinguishing systems as required by SOLAS regulation II-2/7. For the installation of the system, nozzles shall be installed to protect the entire hazard volume (total flooding). The installation specification provided by the manufacturer should include maximum nozzle spacing, maximum enclosure height, distance of nozzles below ceiling, maximum enclosure volume and maximum ventilation condition.

3 SAMPLING

The components to be tested should be supplied by the manufacturer together with design and installation criteria, operational instructions, drawings and technical data sufficient for the identification of the components.

4 METHOD OF TEST

4.1 Principle

This test procedure enables the determination of the effectiveness of different water-based extinguishing systems against spray fires, cascade fires, pool fires and class A fires which are obstructed by an engine mock-up.

4.2 Apparatus

4.2.1 Engine mock-up

The fire test should be performed in a test apparatus consisting of:

.1 An engine mock-up of size (width x length x height) 1 m x 3 m x 3 m constructed of sheet steel with a nominal thickness of 5 mm. The mock-up is fitted with two steel tubes diameter 0.3 m and 3 m length that simulate exhaust manifolds and a grating. At the top of the mock-up a 3 m^2 tray is arranged. See figure 2.

.2 A floor plate system 4 m x 6 m x 0.5 m high surrounding the mock-up with three trays, 2, 2, and 4 m^2, equalling a total area of 8 m^2, underneath. See figure 2.

4.2.2 Test room

.1 Class 1 - Engine-rooms

The test should be performed in 100 m^2 room with 5 m ceiling height and ventilation through a 2 m x 2 m door opening. Fires and engine mock-up according to tables 2, 3 and figure 1.

.2 Class 2 and 3 - Engine-room

The test should be performed in a fire test hall with minimum floor area of 300 m^2, and a ceiling height in excess of 10 m and without any restrictions in air supply for the test fires.

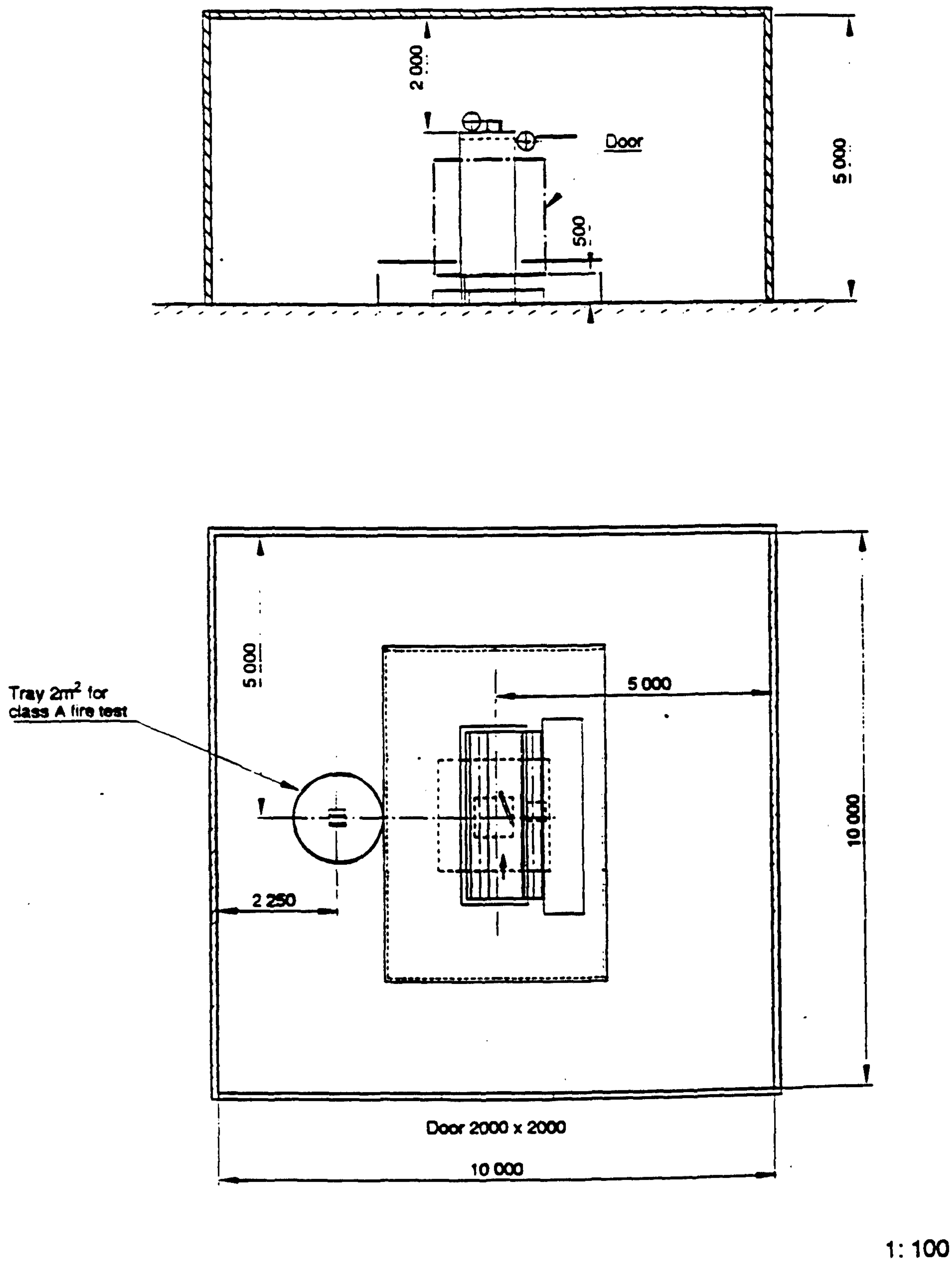
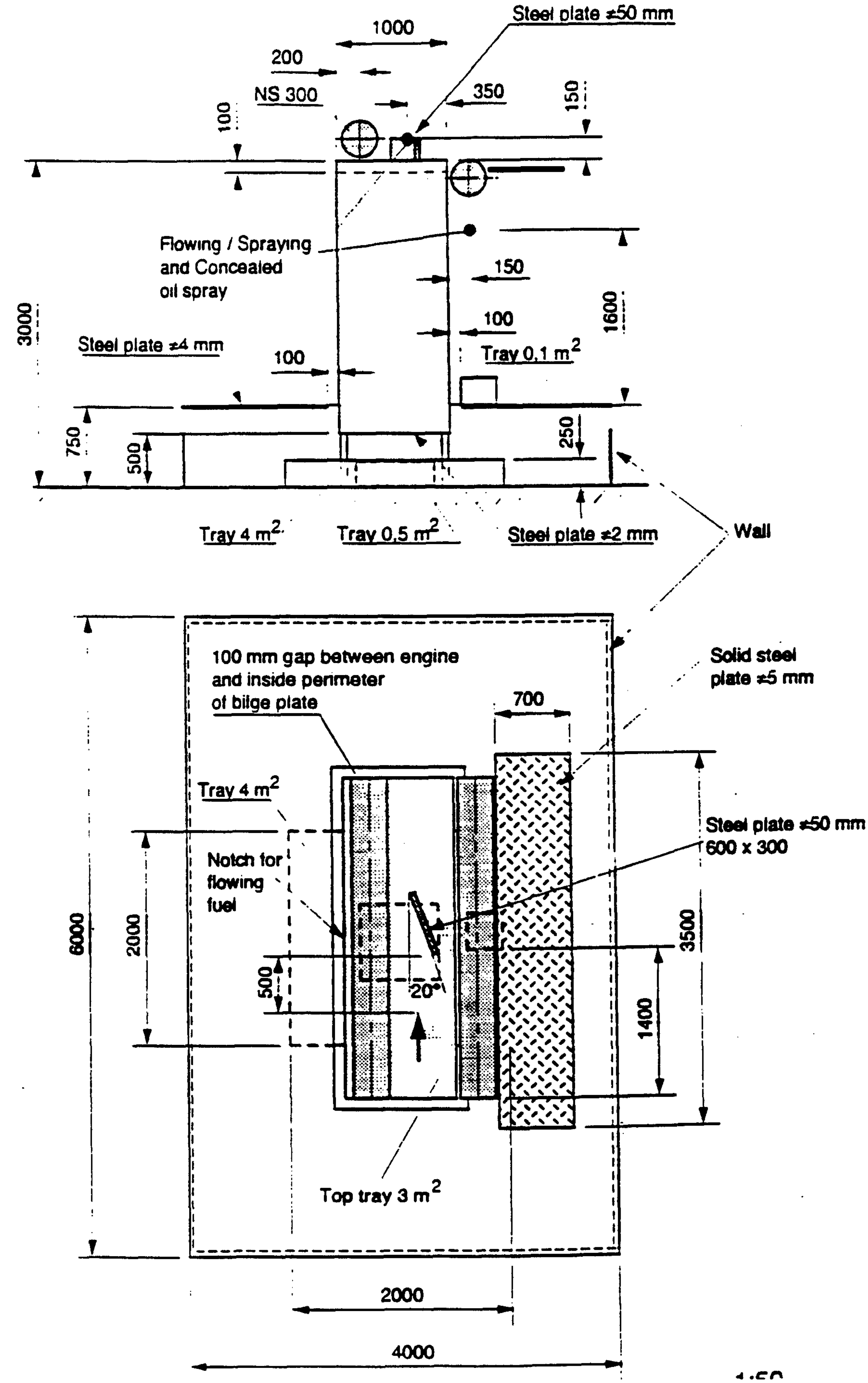
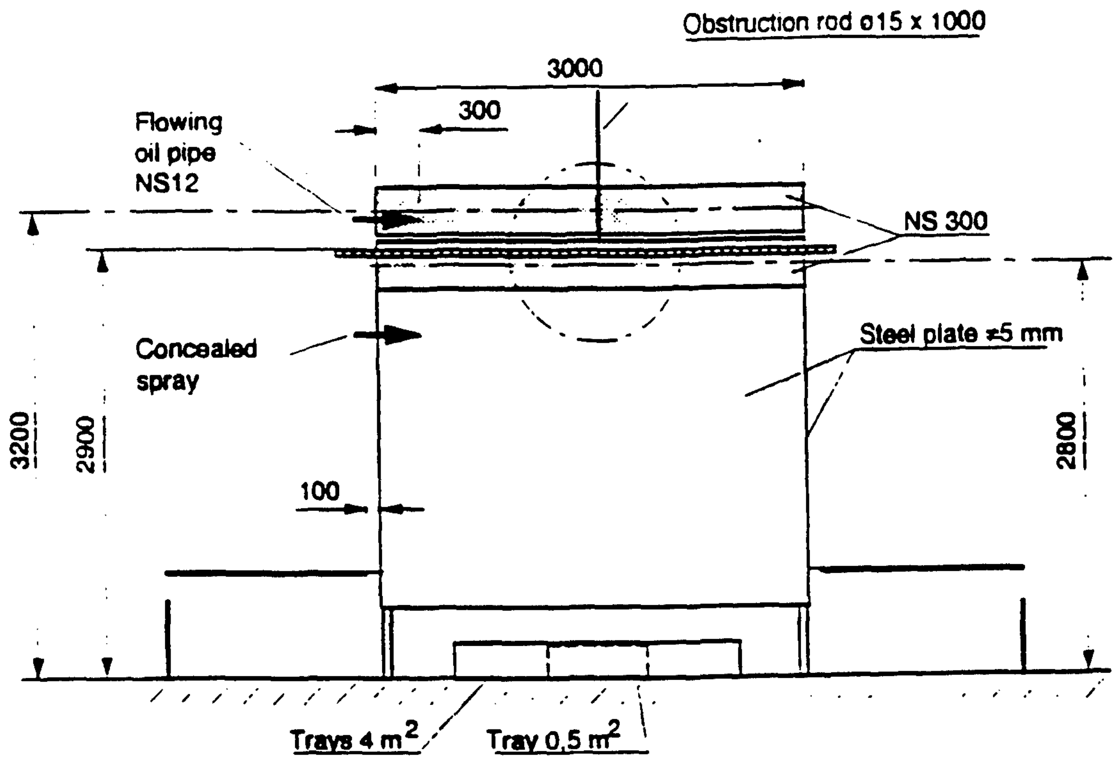

2 000
Door
5 000
500
Tray 2m² for class A fire test
5 000
5 000
10 000
2 250
Door 2000 x 2000
10 000
1: 100

Figure 1


Steel plate ±50 mm
1000
200
NS 300
350
150
100
Flowing / Spraying
and Concealed
oil spray
150
100
1600
3000
Steel plate ±4 mm
100
Tray 0,1 m2
750
500
250
Tray 4 m2
Tray 0,5 m2
Steel plate ±2 mm
Wall
100 mm gap between engine
and inside perimeter
of bilge plate
700
Solid steel
plate ±5 mm
Tray 4 m2
Steel plate ±50 mm
600 x 300
Notch for
flowing
fuel
6000
2000
500
20°
3500
1400
Top tray 3 m2
2000
4000


Obstruction rod ø15 x 1000
3000
300
Flowing
oil pipe
NS12
NS 300
Concealed
spray
Steel plate ≠5 mm
3200
2900
2800
100
Trays 4 m2
Tray 0,5 m2

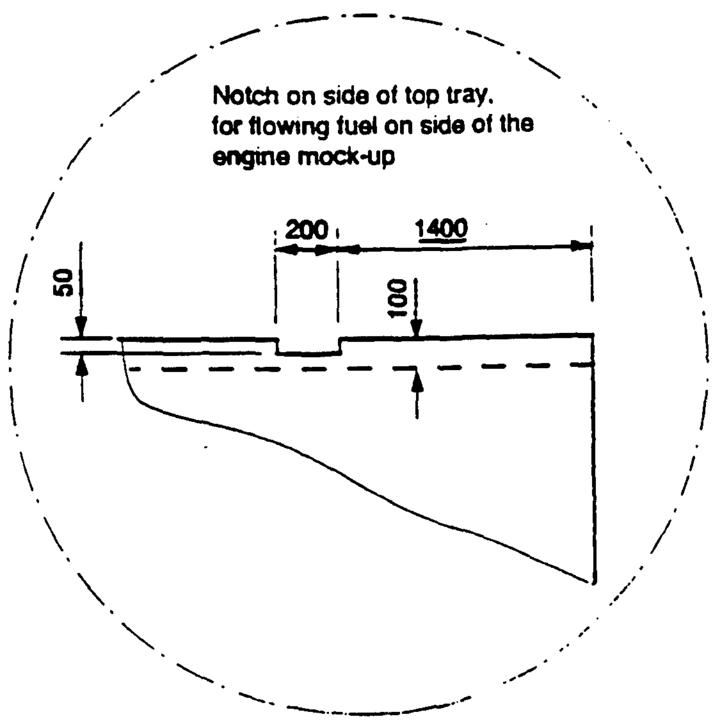

Notch on side of top tray,
for flowing fuel on side of the
engine mock-up
200
1400
50
100

Table 2 - Test programme

Test No.	Fire Scenario	Test Fuel
1	Low pressure horizontal spray on top of simulated engine between agent nozzles	Commercial fuel oil or light diesel oil
2	Low pressure spray on top of simulated engine centred with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1 metre away	Commercial fuel oil or light diesel oil
3	Low pressure concealed horizontal spray fire on side of simulated engine with oil spray nozzle positioned 0.1 m in from the end of engine	Commercial fuel oil or light diesel oil
4	Combination of worst spray fire from Tests 1-3 and fires in trays under (4 m^2) and on top of the simulated engine (3 m^2)	Commercial fuel oil or light diesel oil
5	High pressure horizontal spray fire on top of the simulated engine	Commercial fuel oil or light diesel oil
6	Low pressure low flow concealed horizontal spray fire on the side of simulated engine with oil spray nozzle positioned 0.1 m in from the end of engine and 0.1 m^2 tray positioned 1.4 m in from the engine end at the inside of floor plate	Commercial fuel oil or light diesel oil
7	0.5 m^2 central under mock-up	Heptane
8	0.5 m^2 central under mock-up	SAE 10W30 mineral based lubrication oil
9	0.1 m^2 on top of bilge plate centred under exhaust plate	Heptane
10	Flowing fire 0.25 kg/s from top of mock-up. See figure 3	Heptane
11	Class A fires wood crib (see Note) in 2 m^2 pool fire with 30 sec. preburn. The test tray should be positioned 0.75 m above the floor as shown in figure 2	Heptane
12	A steel plate (30 cm x 60 cm x 5 cm) offset 20° to the spray is heated to 350°C by the top low pressure, low flow spray nozzle positioned horizontally 0.5 m from the front edge of the plate. When the plate reaches 350°C, the system is activated. Following system shut off, no reignition of the spray is permitted	Heptane
13	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil

Note: The wood crib is to weigh 5.4 to 5.9 kg and is to be dimensioned approximately by 305 by 305 by 305 mm. The crib is to consist of eight alternate layers of four trade size 38.1 by 38.1 mm kiln-dried spruce or fir lumber 305 mm long. The alternate layers of the lumber are to be placed at right angles to the adjacent layers. The individual wood members in each layer are to be evenly spaced along the length of the previous layer of wood members and stapled. After the wood crib is assembled, it is to be conditioned at a temperature of 49 +5°C for not less than 16 hours. Following the conditioning, the moisture content of the crib is to be measured with a probe type moisture meter. The moisture content of the crib should not exceed 5% prior to the fire test.

Table 3 - Oil spray fire test parameters

Category A Engine-Room Class 1 - 3			
Fire type	Low pressure	Low pressure, Low flow	High pressure
Spray nozzle	Wide spray angle (120 to 125°) full cone type	Wide spray angle (80°) full cone type	Standard angle (at 6 Bar) full cone type
Nominal oil pressure	8 Bar	8.5 Bar	150 Bar
Oil flow	0.16 ± 0.01 kg/s	0.03 ± 0.005 kg/s	0.050 ± 0.002 kg/s
Oil temperature	20 ± 5°C	20 ± 5°C	20 ± 5°C
Nominal heat release rate	5.8 ± 0.6 MW	1.1 ± 0.1 MW	1.8 ± 0.2 MW

4.3 Extinguishing system

The extinguishing system should be installed according to the manufacturer's design and installation instructions. The maximum vertical distance is limited to 5 m. For actual installation with bilges more than 0.75 m in depth, nozzles must be installed in the bilges in accordance with manufacturer's recommendations as developed from representative fire tests.

4.4 Procedure

4.4.1 Ignition

The tray/s used in the test should be filled with at least 30 mm oil on a water base. Freeboard is to be 150 ± 10 mm.

4.4.2 Flow and pressure measurements (oil system)

The oil flow and pressure in the oil system should be measured before each test. The oil pressure should be measured during the test.

4.4.3 Flow and pressure measurements (extinguishing system)

Agent flow and pressure in the extinguishing system should be measured continuously on the high pressure side of a pump or equivalent equipment at intervals not exceeding 5 seconds during the test, alternatively, the flow can be determined by the pressure and the K factor of the nozzles.

4.4.4 Duration of test

After ignition of all fuel sources, a 2 minute preburn time is required before the extinguishing agent is discharged for the oil tray fires and 5-15 seconds for the oil spray and heptane fires and 30 seconds for the class A fire test (test No.11).

Extinguishing agent should be discharged for 50% of the discharge time recommended by the manufacturer or 15 minutes whatever is less. The oil spray, if used, should be shut off 15 seconds after the end of agent discharge.

4.4.5 Observations before and during the test

Before the test, the test room, fuel and mock-up temperature is to be measured.

During the test the following observations should be recorded:

.1 the start of the ignition procedure;

.2 the start of the test (ignition);

.3 the time when the extinguishing system is activated;

.4 the time when the fire is extinguished, if it is;

.5 the time when the extinguishing system is shut off;

.6 the time of reignition, if any;

.7 the time when the oil flow for the spray fire is shut off; and

.8 the time when the test is finished.

4.4.6 Observations after the test

.1 Damage to any system components;

.2 The level of oil in the tray(s) to make sure that no limitation of fuel occurred during the test.

.3 Test room, fuel and mock-up temperature.

5 CLASSIFICATION CRITERIA

At the end of discharge of water-based fire-extinguishing media and fuel at each test, there should be no re-ignition or fire spread.

6 TEST REPORT

The test report should include the following information:

.1 Name and address of the test laboratory;

.2 Date and identification number of the test report;

.3 Name and address of client;

.4 Purpose of the test;

.5 Method of sampling;

.6 Name and address of manufacturer or supplier of the product;

.7 Name or other identification marks of the product;

.8 Description of the tested product:

- drawings,

- descriptions,

- assembly instructions,

- specification of included materials,

- detailed drawing of test set-up.

.9 Date of supply of the product;

.10 Date of test;

.11 Test method;

.12 Drawing of each test configuration;

.13 Measured nozzle characteristics;

.14 Identification of the test equipment and used instruments;

.15 Conclusions;

.16 Deviations from the test method, if any;

.17 Test results including observations during and after the test; and

.18 Date and signature.

Appendix B

Instrumentation and Camera Details

F.I.R.E.S. FORM #1

TEST NAME: Water Mist Testing
(30 character maximum)
TEST SERIES: 98 WM
(4 character maximum)
TOTAL NUMBER OF TESTS: _
PROJECT NUMBER: ____________

INSTRUMENT LIST &
TEST REQUIREMENTS

TIME FOR EACH TEST
TEST: 20 MINUTES
SCAN INTERVAL: 6 SECONDS

CHANNEL				INSTRUMENT DESCRIPTION	SERIAL NUMBER	OUTPUT RANGE	LOCATION (x, y, z)	REMARKS/NOTES
#	SP	RE	ID			ENG. UNIT		
0				Humidity	J4-3543	0-100% R.H.	Near Trailer	Ambient
1				Barometer	123	91-106 kPa	Near Trailer	Ambient
2				Wind—Intensity	04401A-I	0-44.5 MB	High spot on ship	Ambient
3				Wind—Direction	04401A-D	0-360°	High spot on ship	Ambient 0° = bow of ship
4				TC reference junction	TC1	0-50°C	Near Trailer	
5		4	X	TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 0.3)	TC Tree 1
6		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 0.91)	TC Tree 1
7		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 1.52)	TC Tree 1
8		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 2.13)	TC Tree 1
9		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 2.74)	TC Tree 1
10		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 3.35)	TC Tree 1
11		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 3.96)	TC Tree 1
12		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 4.57)	TC Tree 1
13		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 5.18)	TC Tree 1

TEST NAME: Water Mist

F.I.R.E.S. FORM #1

CHANNEL				INSTRUMENT DESCRIPTION	SERIAL NUMBER	OUTPUT RANGE	LOCATION (x, y, z)	REMARKS/NOTES
#	SP	RE	ID			ENG. UNIT		
14		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 5.79)	TC Tree 1
15		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 6.4)	TC Tree 1
16		4		TC	K 25 ft, 1/8-in.	0-1000°C	(1.0, 3.35, 7.01)	TC Tree 1
17		4		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 0.3)	TC Tree 2
18		4		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 0.91)	TC Tree 2
19		4		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 1.52)	TC Tree 2
20		4		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 2.13)	TC Tree 2
21		4		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 2.74)	TC Tree 2
22		4		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 3.35)	TC Tree 2
23		4		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 3.96)	TC Tree 2
24		4		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 4.57)	TC Tree 2
25				TC reference junction	TC2	0-50°C	TC junction box	
26		25		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 5.18)	TC Tree 2
27		25		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 5.79)	TC Tree 2
28		25		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 6.4)	TC Tree 2
29		25		TC	K 25 ft, 1/8-in.	0-1000°C	(6.1, 3.35, 7.01)	TC Tree 2
30		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 0.3)	TC Tree 3
31		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 0.91)	TC Tree 3
32		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 1.52)	TC Tree 3
33		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 2.13)	TC Tree 3

TEST NAME: Water Mist   F.I.R.E.S. FORM #1

CHANNEL				INSTRUMENT DESCRIPTION	SERIAL NUMBER	OUTPUT RANGE	LOCATION (x, y, z)	REMARKS/NOTES
#	SP	RE	ID			ENG. UNIT		
34		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 2.74)	TC Tree 3
35		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 3.35)	TC Tree 3
36		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 3.96)	TC Tree 3
37		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 4.57)	TC Tree 3
38		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 5.18)	TC Tree 3
39		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 5.79)	TC Tree 3
40		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 6.4)	TC Tree 3
41		25		TC	K 25 ft, 1/8-in.	0-1000°C	(9.1, 3.35, 7.01)	TC Tree 3
42			X	CO analyzer	41092	0-10%	(10.1, 3.35, 1.5)	Gas Tree
43			X	CO_2 analyzer	30606	0-25%	(10.1, 3.35, 1.5)	Gas Tree
44			X	O_2 analyzer	1001451	0-25%	(10.1, 3.35, 1.5)	Gas Tree
45				CO analyzer	41093	0-10%	(10.1, 3.35, 3.0)	Gas Tree
46				CO_2 analyzer	31334	0-25%	(10.1, 3.35, 3.0)	Gas Tree
47				O_2 analyzer	1001637	0-25%	(10.1, 3.35, 3.0)	Gas Tree
48				CO analyzer	41094	0-10%	(10.1, 3.35, 4.5)	Gas Tree
49				CO_2 analyzer	31335	0-25%	(10.1, 3.35, 4.5)	Gas Tree
50				O_2 analyzer	1001638	0-25%	(10.1, 3.35, 4.5)	Gas Tree
51				CO analyzer		0-10%	(10.1, 3.35, 6.0)	Gas Tree
52				CO_2 analyzer	41347	0-25%	(10.1, 3.35, 6.0)	Gas Tree
53				O_2 analyzer	34056	0-25%	(10.1, 3.35, 6.0)	Gas Tree

TEST NAME: Water Mist F.I.R.E.S. FORM #1

CHANNEL				INSTRUMENT DESCRIPTION	SERIAL NUMBER	OUTPUT RANGE	LOCATION (x, y, z)	REMARKS/NOTES
#	SP	RE	ID			ENG. UNIT		
54				O_2 analyzer	1001641	0-25%	(6.0, 3.35, 2.0)	Fire location
55			X	Radiometer	2002456	0-50 kW/m^2	(5.5, 6.7, 1.5)	in port bulkhead
56			X	Calorimeter	219858	0-100 kW/m^2	(5.5, 6.7, 1.5)	in port bulkhead
57				Radiometer	68211	0-100 kW/m^2	(5.5, 6.7, 3.0)	in port bulkhead
58				Calorimeter	68211	0-100 kW/m^2	(5.5, 6.7, 3.0)	in port bulkhead
59				Radiometer	68215	0-100 kW/m^2	(5.5, 6.7, 5.13)	in port bulkhead
60				Calorimeter	682112	0-100 kW/m^2	(5.5, 6.7, 5.13)	in port bulkhead
61				Radiometer	87621	0-100 kW/m^2	(5.5, 6.7, 6.61)	in port bulkhead
62				Calorimeter	68214	0-100 kW/m^2	(5.5, 6.7, 6.61)	in port bulkhead
63			X	Pressure transducer	98220	689 kPa		on heptane line
64				TC reference junction	TC3	0-50°C	TC junction box	
65		64		TC	KXCEFIRSXWLD	0-1000°C	(0.5, 6.2, 0.45)	tell-tail tree #1
66		64		TC	KXCEFIRSXWLD	0-1000°C	(0.5, 6.2, 1.67)	tell-tail tree #1
67		64		TC	KXCEFIRSXWLD	0-1000°C	(0.5, 6.2, 2.89)	tell-tail tree #1
68		64		TC	KXCEFIRSXWLD	0-1000°C	(0.5, 6.2, 4.11)	tell-tail tree #1
69		64		TC	KXCEFIRSXWLD	0-1000°C	(0.5, 6.2, 5.33)	tell-tail tree #1
70		64		TC	KXCEFIRSXWLD	0-1000°C	(0.5, 6.2, 6.55)	tell-tail tree #1
71		64		TC	KXCEFIRSXWLD	0-800°C	(5.1, 0.5, 0.45)	tell-tail tree #2
72		64		TC	KXCEFIRSXWLD	0-800°C	(5.1, 0.5, 1.67)	tell-tail tree #2
73		64		TC	KXCEFIRSXWLD	0-800°C	(5.1, 0.5, 2.89)	tell-tail tree #2

TEST NAME: Water Mist

F.I.R.E.S. FORM #1

CHANNEL				INSTRUMENT DESCRIPTION	SERIAL NUMBER	OUTPUT RANGE	LOCATION (x, y, z)	REMARKS/NOTES
#	SP	RE	ID			ENG. UNIT		
74		64		TC	KXCEFIRSXWLD	0-800°C	(5.1, 0.5, 4.11)	tell-tail tree #2
75		64		TC	KXCEFIRSXWLD	0-800°C	(5.1, 0.5, 5.33)	tell-tail tree #2
76		64		TC	KXCEFIRSXWLD	0-800°C	(5.1, 0.5, 6.55)	tell-tail tree #2
77				TC reference junction	TC4	0-50°C	TC junction box	
78		77		TC	K50FT1/8IN	0-800°C	(4.7, 2.5, 3.0)	top of engine mock-up
79		77		TC	K50FT1/8IN	0-800°C	(4.7, 2.5, 3.0)	top of engine mock-up
80		77		TC	K50FT1/8IN	0-800°C	(4.7, 1.75, 2.0)	side middle of engine mock-up
81		77		TC	K50FT1/8IN	0-800°C	(4.7, 1.75, 2.0)	side middle of engine mock-up
82		77		TC	K50FT1/8IN	0-800°C	(4.7, 1.75, 1.0)	side bottom of engine mock-up
83		77		TC	K50FT1/8IN	0-800°C	(4.7, 1.75, 1.0)	side bottom of engine mock-up
84				Smoke density laser	685594	Transmitting 0-100%	(11.0, 0.1, 2.0)	starboard FWD corner
85				Smoke density laser	631964	Transmitting 0-100%	(11.0, 0.1, 4.0)	starboard FWD corner
86				Smoke density laser	564851	Transmitting 0-100%	(11.0, 0.1, 6.0)	starboard FWD corner
87				Pressure transducer	D1	0-20658 kPa	main deck	pump manifold (lower)
88				Pressure transducer	D2	0-20658 kPa	pipe network	pipe network pressure (lower)
89				Pressure transducer	D3	0-20658 kPa	main deck	pump manifold (high)
90				Pressure transducer	D4	0-20658 kPa	pipe network	pipe network pressure (high)
91				Pressure transducer	139966	0-1723 kPa	main deck	pump manifold (lower)

TEST NAME: Water Mist

F.I.R.E.S. FORM #1

CHANNEL				INSTRUMENT DESCRIPTION	SERIAL NUMBER	OUTPUT RANGE	LOCATION (x, y, z)	REMARKS/NOTES
#	SP	RE	ID			ENG. UNIT		
92				Pressure transducer	139967	0-1723 kPa	pipe network	pipe network pressure (lower)
93				Pressure transducer	139968	0-1723 kPa	main deck	pump manifold (high)
94				Pressure transducer	139969	0-1723 kPa	pipe network	pipe network pressure (high)
** ACTUATIONS ** Sound a remote alarm if scanning stops; Time-Date Generator starts at "ignition" stop size								

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Appendix C

Test Data

List of Tests Conducted

Test Number	Mist System	Fire Size	Fuel Type	Location	Nozzle Elevation	Vent Configuration	Page Number
1	Freeburn	1. 0 MW	Spray Heptane	Top		IMO	
2	Spraying Systems	1.0 MW	Spray Heptane	Top	5.0 m	IMO	
3	Spraying Systems	2.0 MW	Spray Heptane	Top	5.0 m	IMO	
4	Spraying Systems	6.0 MW	Spray Heptane	Top	5.0 m	IMO	
5	Grinnell	1.0 MW	Spray Heptane	Top	5.0 m	IMO	
6	Grinnell	1.0 MW	Reignition Heptane	Top	5.0 m	IMO	
7	Grinnell	1.0 MW	Reignition Heptane	Top	5.0 m	IMO	
8	Grinnell	2.0 MW	Spray Heptane	Top	5.0 m	IMO	
9	Grinnell	2.0 MW	Spray Heptane	Top	5.0 m	IMO	
10	Grinnell	6.0 MW	Spray Heptane	Top	5.0 m	IMO	
11	Grinnell	1.0 MW	Spray Heptane	Side	5.0 m	IMO	
12	Grinnell	0.5 MW	Pan Heptane	Bilge	5.0 m	IMO	
13	Grinnell	$0.1 m^2$	Pan Heptane	Side	5.0 m	IMO	
14	Grinnell	$3 m^2$	Pan Heptane	Top	5.0 m	IMO	
15	Grinnell	$3 m^2$ +	Flowing Heptane	Top	5.0 m	IMO	
16	Grinnell	6.0 MW	Spray Heptane	Side	5.0 m	IMO	
17	Grinnell	$0.5 m^2$	Pan 10W30 Oil	Bilge	5.0 m	IMO	
18	Grinnell	1.0 MW	Spray Diesel	Side	5.0 m	IMO	

Test Number	Mist System	Fire Size	Fuel Type	Location	Nozzle Elevation	Vent Configuration	Page Number
19	Grinnell	2.0 MW	Spray Diesel	Top	5.0 m	IMO	
20	Grinnell	6.0 MW	Spray Diesel	Top	5.0 m	IMO	
21	Grinnell	6.0 MW	Spray Diesel	Top	5.0 m	IMO & Roof Vent	
22	Grinnell	6.0 MW	Spray Diesel	Top	5.0 m	IMO & Roof Vent	
23	Grinnell	2.0 MW	Spray Diesel	Top	5.0 m	IMO & Roof Vent	
24	Grinnell	6.0 MW	Spray Diesel	Side	5.0 m	IMO & Roof Vent	
25	Grinnell	4.0 MW	Spray Diesel	Top	5.0 m	IMO & Roof Vent	
26	Grinnell	4.0 MW	Spray Diesel	Top	5.0 m	IMO & Roof Vent	
27	Grinnell	6.0 MW	Spray Heptane	Top	5.0 m	IMO & Roof Vent	
28	Grinnell	3.0 m^2	Pan Heptane	Top	5.0 m	IMO & Roof Vent	
29	Grinnell	6.0 MW	Spray Heptane	Top	7.0 m	IMO	
30	Grinnell	2.0 MW	Spray Heptane	Top	7.0 m	IMO	
31	Grinnell	1.0 MW	Spray Heptane	Top	7.0 m	IMO	
32	Grinnell	3.0 m^2	Pan Heptane	Top	7.0 m	IMO	
33	Grinnell	6.0 MW	Spray Heptane	Side	7.0 m	IMO	
34	Grinnell	1.0 MW	Spray Heptane	Side	7.0 m	IMO	
35	Grinnell	1.0 MW	Spray Diesel	Side	7.0 m	IMO	
36	Grinnell	6.0 MW	Spray Diesel	Side	7.0 m	IMO	
37	Grinnell	6.0 MW	Spray Diesel	Top	7.0 m	IMO	

Test Number	Mist System	Fire Size	Fuel Type	Location	Nozzle Elevation	Vent Configuration	Page Number
38	Grinnell	2.0 MW	Spray Diesel	Top	7.0 m	IMO	
39	Grinnell	6.0 MW	Spray Diesel	Top	7.0 m	IMO & Roof Vent	
40	Grinnell	2.0 MW	Spray Diesel	Top	7.0 m	IMO & Roof Vent	
41	Grinnell	6.0 MW	Spray Diesel	Side	7.0 m	IMO & Roof Vent	
42	Grinnell	6.0 MW	Spray Heptane	Top	7.0 m	IMO & Roof Vent	
43	Spraying Systems	6.0 MW	Spray Heptane	Top	5.0 m	IMO	
44	Spraying Systems	1.0 MW	Reigntion Heptane	Top	5.0 m	IMO	
45	Spraying Systems	1.0 MW	Pan Heptane	Top	5.0 m	IMO	
46	Spraying Systems	6.0 MW	Spray Heptane	Side	5.0 m	IMO	
47	Spraying Systems	1.0 MW	Spray Heptane	Side	5.0 m	IMO	
48	Spraying Systems	6.0 MW	Spray Diesel	Side	5.0 m	IMO	
49	Spraying Systems	1.0 MW	Spray Diesel	Side	5.0 m	IMO	
50	Spraying Systems	2.0 MW	Spray Diesel	Top	5.0 m	IMO	
51	Spraying Systems	6.0 MW	Spray Diesel	Top	5.0 m	IMO	
52	Spraying Systems	0.1 m^2	Pan Heptane	Side	5.0 m	IMO	
53	Spraying Systems	0.5 m^2	Pan 10W30 Oil	Bilge	5.0 m	IMO	
54	Spraying Systems	6.0 MW	Spray Diesel	Top	5.0 m	IMO & Roof Vent	
55	Spraying Systems	2.0 MW	Spray Diesel	Top	5.0 m	IMO & Roof Vent	
56	Spraying Systems	6.0 MW	Spray Diesel	Side	5.0 m	IMO & Roof Vent	

Test Number	Mist System	Fire Size	Fuel Type	Location	Nozzle Elevation	Vent Configuration	Page Number
57	Spraying Systems	6.0 MW	Spray Heptane	Top	5.0 m	IMO & Roof Vent	
58	Spraying Systems	3.0 m^2	Pan Heptane	Top	5.0 m	IMO & Roof Vent	
59	Spraying Systems	1.0 MW	Reignition Heptane	Top	7.0 m	IMO	
60	Spraying Systems	1.0 MW	Spray Heptane	Top	7.0 m	IMO	
61	Spraying Systems	6.0 MW	Spray Heptane	Top	7.0 m	IMO	
62	Spraying Systems	2.0 MW	Spray Heptane	Top	7.0 m	IMO	
63	Spraying Systems	6.0 MW	Spray Heptane	Side	7.0 m	IMO	
64	Spraying Systems	1.0 MW	Spray Heptane	Side	7.0 m	IMO	
65	Spraying Systems	1.0 MW	Spray Diesel	Side	7.0 m	IMO	
66	Spraying Systems	6.0 MW	Spray Diesel	Side	7.0 m	IMO	
67	Spraying Systems	2.0 MW	Spray Diesel	Top	7.0 m	IMO	
68	Spraying Systems	6.0 MW	Spray Diesel	Top	7.0 m	IMO	
69	Spraying Systems	0.1 m^2	Pan Heptane	Side	7.0 m	IMO	
70	Spraying Systems	0.5 m^2	Pan 10W30 Oil	Bilge	7.0 m	IMO	
71	Spraying Systems	3.0 m^2	Pan Heptane	Top	7.0 m	IMO	
72	Spraying Systems	6.0 MW	Spray Diesel	Top	7.0 m	IMO & Roof Vent	
73	Spraying Systems	2.0 MW	Spray Diesel	Top	7.0 m	IMO & Roof Vent	
74	Spraying Systems	6.0 MW	Spray Diesel	Side	7.0 m	IMO & Roof Vent	
75	Spraying Systems	6.0 MW	Spray Diesel	Top	7.0 m	IMO & Roof Vent	

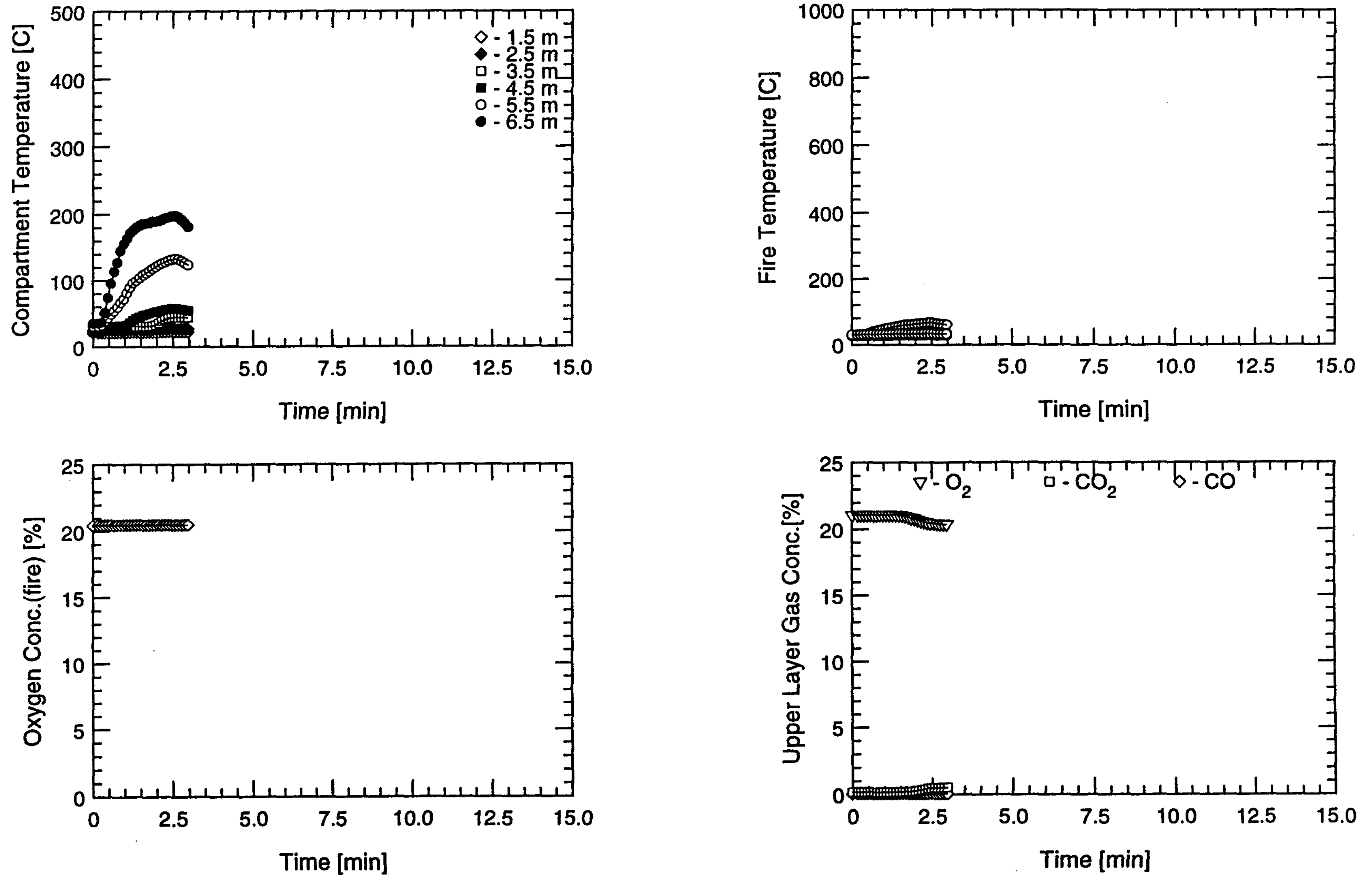
Test Number	Mist System	Fire Size	Fuel Type	Location	Nozzle Elevation	Vent Configuration	Page Number
76	Spraying Systems	1.0 MW	Reignition Heptane	Top	7.0 m	IMO & Roof Vent	
77	Spraying Systems	3.0 m^2	Pan Heptane	Top	7.0 m	IMO & Roof Vent	
78	Freeburn	6.0 MW	Spray Heptane	Top	7.0 m	IMO	
79	Reliable	6.0 MW	Spray Heptane	Top	7.0 m	IMO	
80	Reliable	6.0 MW	Spray Heptane	Top	7.0 m	IMO	
81	Reliable	2.0 MW	Spray Heptane	Top	7.0 m	IMO	
82	Reliable	1.0 MW	Reignition Heptane	Top	7.0 m	IMO	
83	Reliable	6.0 MW	Spray Heptane	Side	7.0 m	IMO	
84	Reliable	6.0 MW	Spray Heptane	Side	7.0 m	IMO	
85	Reliable	1.0 MW	Spray Heptane	Side	7.0 m	IMO	
86	Reliable	3 m^2	Pan Heptane	Top	7.0 m	IMO	
87	Reliable	6.0 MW	Spray Diesel	Top	7.0 m	IMO	
88	Reliable	6.0 MW	Spray Diesel	Top	7.0 m	IMO	
89	Reliable	2.0 MW	Spray Diesel	Top	7.0 m	IMO	
90	Reliable	1.0 MW	Spray Diesel	Top	7.0 m	IMO	
91	Reliable	1.0 MW	Spray Diesel	Top	7.0 m	IMO	
92	Reliable	6.0 MW	Spray Diesel	Side	7.0 m	IMO	
93	Reliable	1.0 MW	Spray Diesel	Side	7.0 m	IMO	
94	Reliable	0.5 m^2	Pan Heptane	Side	7.0 m	IMO	

Test Number	Mist System	Fire Size	Fuel Type	Location	Nozzle Elevation	Vent Configuration	Page Number
95	Reliable	6.0 MW	Spray Diesel	Top	7.0 m	IMO & Roof Vent	
96	Kidde-Fenwal	6.0 MW	Spray Diesel	Top	7.0 m	IMO	
97	Kidde-Fenwal	2.0 MW	Spray Diesel	Top	7.0 m	IMO	
98	Kidde-Fenwal	6.0 MW	Spray Diesel	Side	7.0 m	IMO	
99	Kidde-Fenwal	1.0 MW	Spray Diesel	Side	7.0 m	IMO	
100	Kidde-Fenwal	6.0 MW	Spray Heptane	Side	7.0 m	IMO	
101	Kidde-Fenwal	1.0 MW	Spray Heptane	Side	7.0 m	IMO	
102	Kidde-Fenwal	0.5 m^2	Pan Heptane	Side	7.0 m	IMO	
103	Kidde-Fenwal	0.5 m^2	Pan Heptane	Side	7.0 m	IMO	
104	Kidde-Fenwal	6.0 MW	Spray Heptane	Top	7.0 m	IMO	
105	Kidde-Fenwal	2.0 MW	Spray Heptane	Top	7.0 m	IMO	
106	Kidde-Fenwal	1.0 MW	Spray Heptane	Top	7.0 m	IMO	
107	Kidde-Fenwal	3 m^2	Pan Heptane	Top	7.0 m	IMO	
108	Kidde-Fenwal	0.1 m^2	Pan Heptane	Side	7.0 m	IMO	
109	Securiplex	6.0 MW	Spray Heptane	Top	6.5 m	IMO	
110	Securiplex	2.0 MW	Spray Heptane	Top	6.5 m	IMO	
111	Securiplex	1.0 MW	Spray Diesel	Top	6.5 m	IMO	
112	Securiplex	2.0 MW	Spray Diesel	Top	6.5 m	IMO	
113	Securiplex	6.0 MW	Spray Diesel	Top	6.5 m	IMO	

Test Number	Mist System	Fire Size	Fuel Type	Location	Nozzle Elevation	Vent Configuration	Page Number
114	Securiplex	3 m^2	Pan Heptane	Top	6.5 m	IMO	
115	Securipex	6.0 MW	Spray Diesel	Side	6.5 m	IMO	
116	Securiplex	1.0 MW	Spray Diesel	Side	6.5 m	IMO	
117	Securiplex	1.0 MW	Spray Heptane	Side	6.5 m	IMO	
118	Securiplex	6.0 MW	Spray Heptane	Side	6.5 m	IMO	
119	Securiplex	0.5 m^2	Pan Heptane	Side	6.5 m	IMO	
120	Spraying Systems (T Series)	6.0 MW	Spray Heptane	Top	7.0 m	IMO	
121	Spraying Systems (T Series)	2.0 MW	Spray Heptane	Top	7.0 m	IMO	
122	Spraying Systems (T Series)	1.0 MW	Spray Heptane	Top	7.0 m	IMO	
123	Spraying Systems (T Series)	0.6 MW	Spray Heptane	Top	7.0 m	IMO	
124	Spraying Systems (T Series)	0.8 MW	Spray Heptane	Top	7.0 m	IMO	
125	Spraying Systems (T Series)	6.0 MW	Spray Heptane	Side	7.0 m	IMO	
126	Spraying Systems (T Series)	2.0 MW	Spray Heptane	Side	7.0 m	IMO	
127	Spraying Systems (T Series)	1.0 MW	Spray Heptane	Side	7.0 m	IMO	
128	Spraying Systems (T Series)	0.8 MW	Spray Heptane	Side	7.0 m	IMO	
129	Spraying Systems (T Series)	0.8 MW	Spray Heptane	Side	7.0 m	IMO	
130	Spraying Systems (T Series)	0.1 m^2	Pan Heptane	Top	7.0 m	IMO	
131	Spraying Systems (T Series)	0.5 m^2	Pan Heptane	Top	7.0 m	IMO	
132	Spraying Systems (T Series)	1.0 m^2	Pan Heptane	Top	7.0 m	IMO	

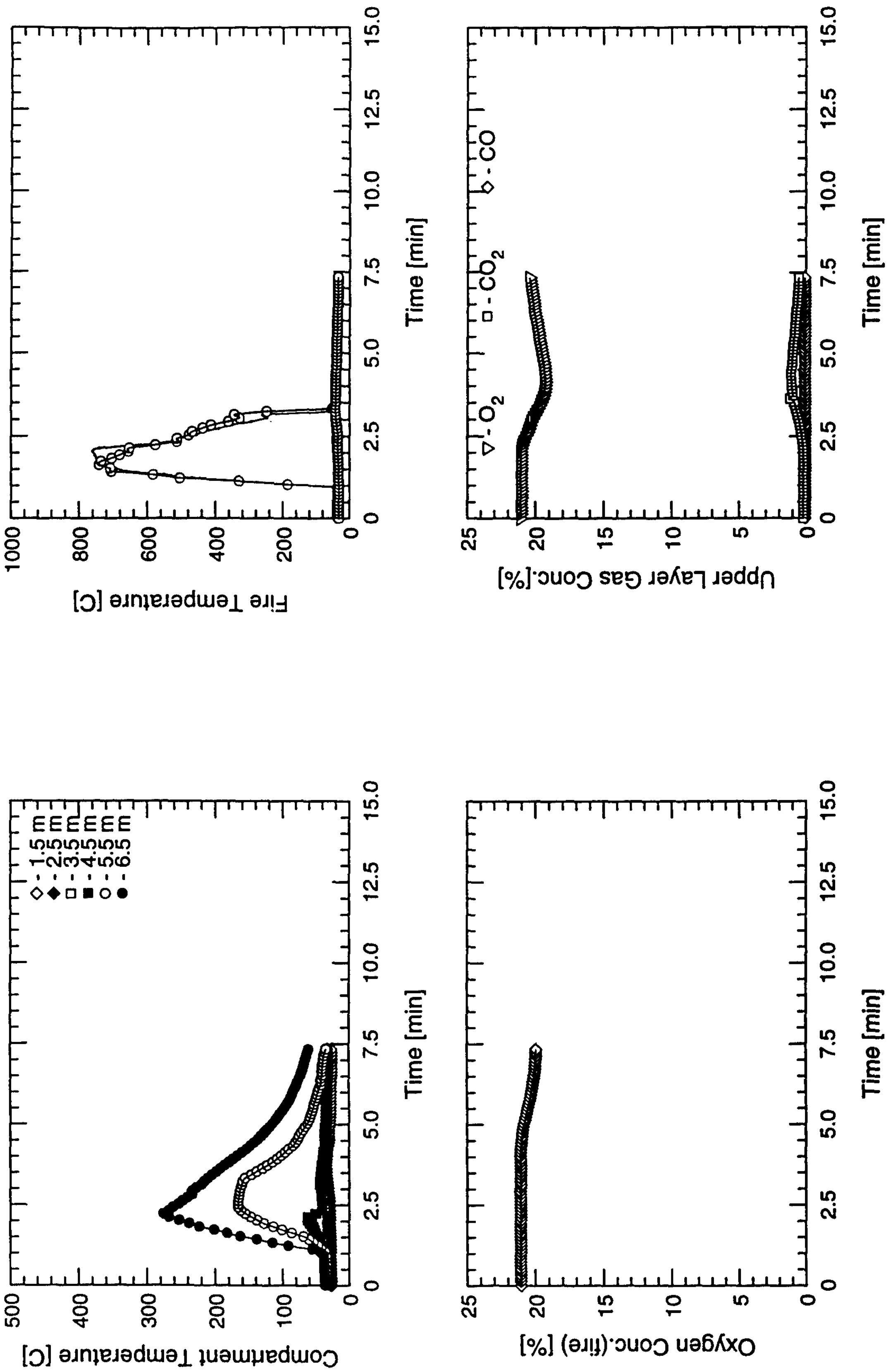
Test Number	Mist System	Fire Size	Fuel Type	Location	Nozzle Elevation	Vent Configuration	Page Number
133	Spraying Systems (T Series)	3.0 m^2	Pan Heptane	Top	7.0 m	IMO	
134	Spraying Systems (T Series)	1.0 m^2	Pan Heptane	Below	7.0 m	IMO	
135	Spraying Systems (T Series)	0.5 m^2	Pan Heptane	Below	7.0 m	IMO	
136	Spraying Systems (T Series)	0.1 m^2	Pan Heptane	Below	7.0 m	IMO	
137	Spraying Systems (T Series)	1.0 m^2	Pan Heptane	Side	7.0 m	IMO	
138	Spraying Systems (T Series)	0.5 m^2	Pan Heptane	Side	7.0 m	IMO	
139	Spraying Systems (T Series)	6.0 MW	Spray Heptane	Top	5.0/7.0 m	IMO	
140	Spraying Systems (T Series)	2.0 MW	Spray Heptane	Top	5.0/7.0 m	IMO	
141	Spraying Systems (T Series)	0.8 MW	Spray Heptane	Top	5.0/7.0 m	IMO	
142	Spraying Systems (T Series)	0.5 m^2	Pan Heptane	Top	5.0/7.0 m	IMO	
143	Spraying Systems (T Series)	6.0 MW	Spray Heptane	Side	5.0/7.0 m	IMO	
144	Spraying Systems (T Series)	2.0 MW	Spray Heptane	Side	5.0/7.0 m	IMO	
145	Spraying Systems (T Series)	0.8 MW	Spray Heptane	Side	5.0/7.0 m	IMO	
146	Spraying Systems (T Series)	0.5 m^2	Pan Heptane	Side	5.0/7.0 m	IMO	
147	Spraying Systems (T Series)	0.5 m^2	Pan Heptane	Low	5.0/7.0 m	IMO	
148	Spraying Systems (T Series)	0.5 m^2	Pan Heptane	Top	5.0/7.0 m	IMO	
149	Spraying Systems (T Series)	0.5 m^2	Pan Heptane	Low	5.0/7.0 m	IMO & Roof Vent	
150	Spraying Systems (T Series)	6.0 MW	Spray Heptane	Top	5.0/7.0 m	IMO & Roof Vent	
151	Spraying Systems (T Series)	2.0 MW	Spray Heptane	Top	5.0/7.0 m	IMO & Roof Vent	

Test Number	Mist System	Fire Size	Fuel Type	Location	Nozzle Elevation	Vent Configuration	Page Number
152	Spraying Systems (T Series)	0.8 MW	Spray Heptane	Top	5.0/7.0 m	IMO & Roof Vent	
153	Spraying Systems (T Series)	0.5 m^2	Pan Heptane	Top	5.0/7.0 m	IMO & Roof Vent	
154	Spraying Systems (T Series)	3 m^2	Pan Heptane	Top	5.0/7.0 m	IMO & Roof Vent	



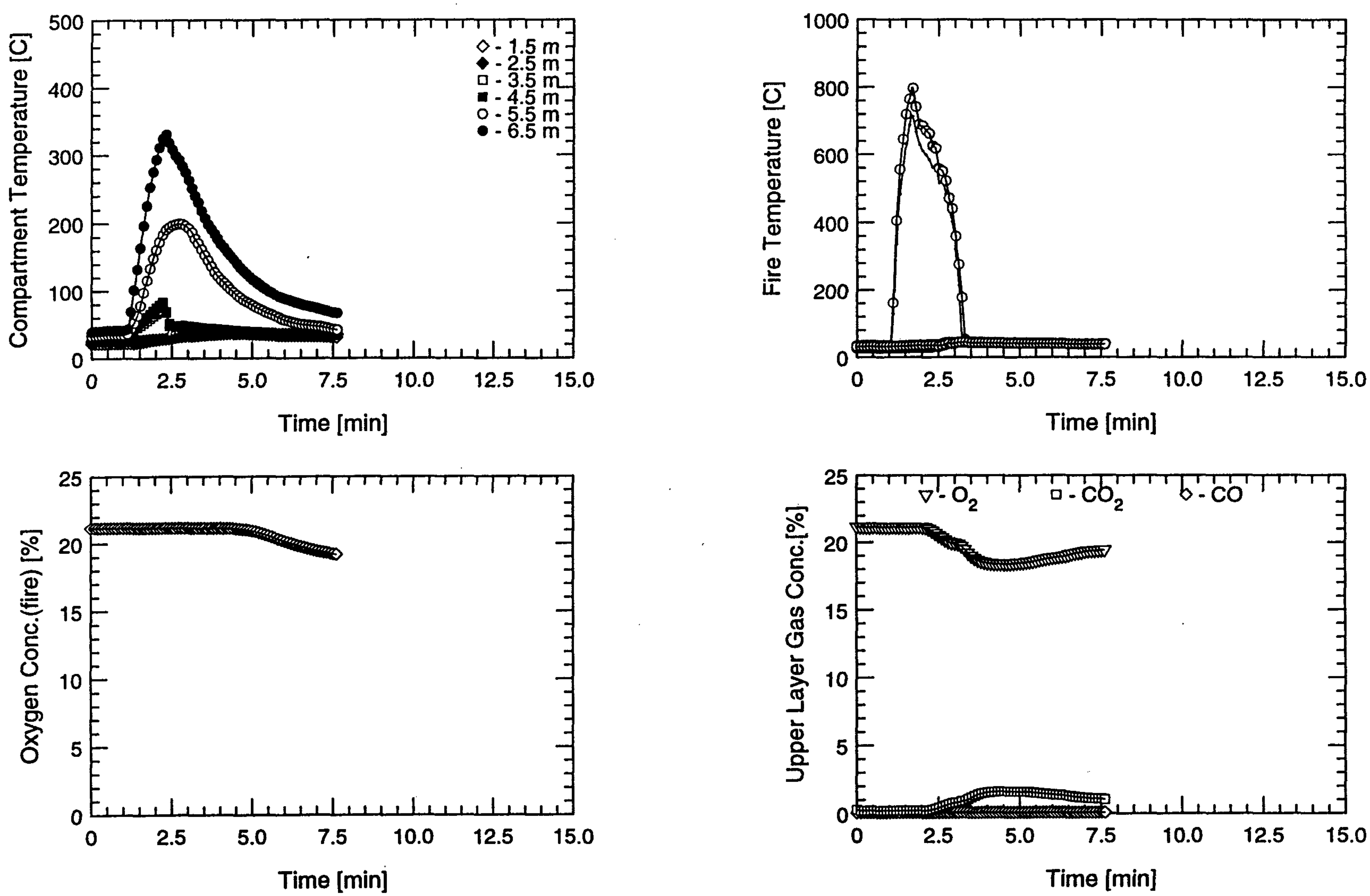
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
0
2.5
5.0
7.5
10.0
12.5
15.0
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #1



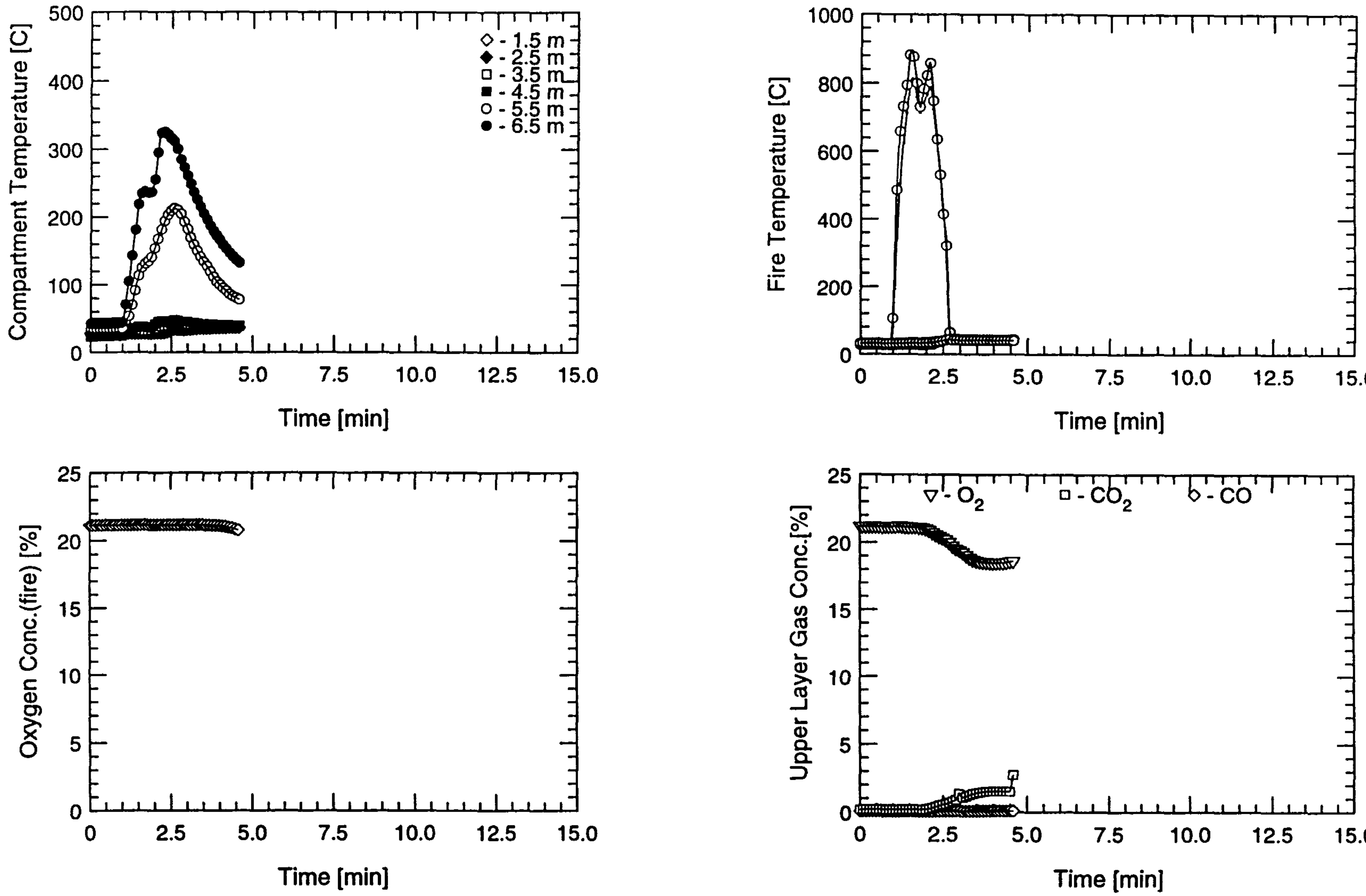
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Oxygen Conc.(fire) [%]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #2

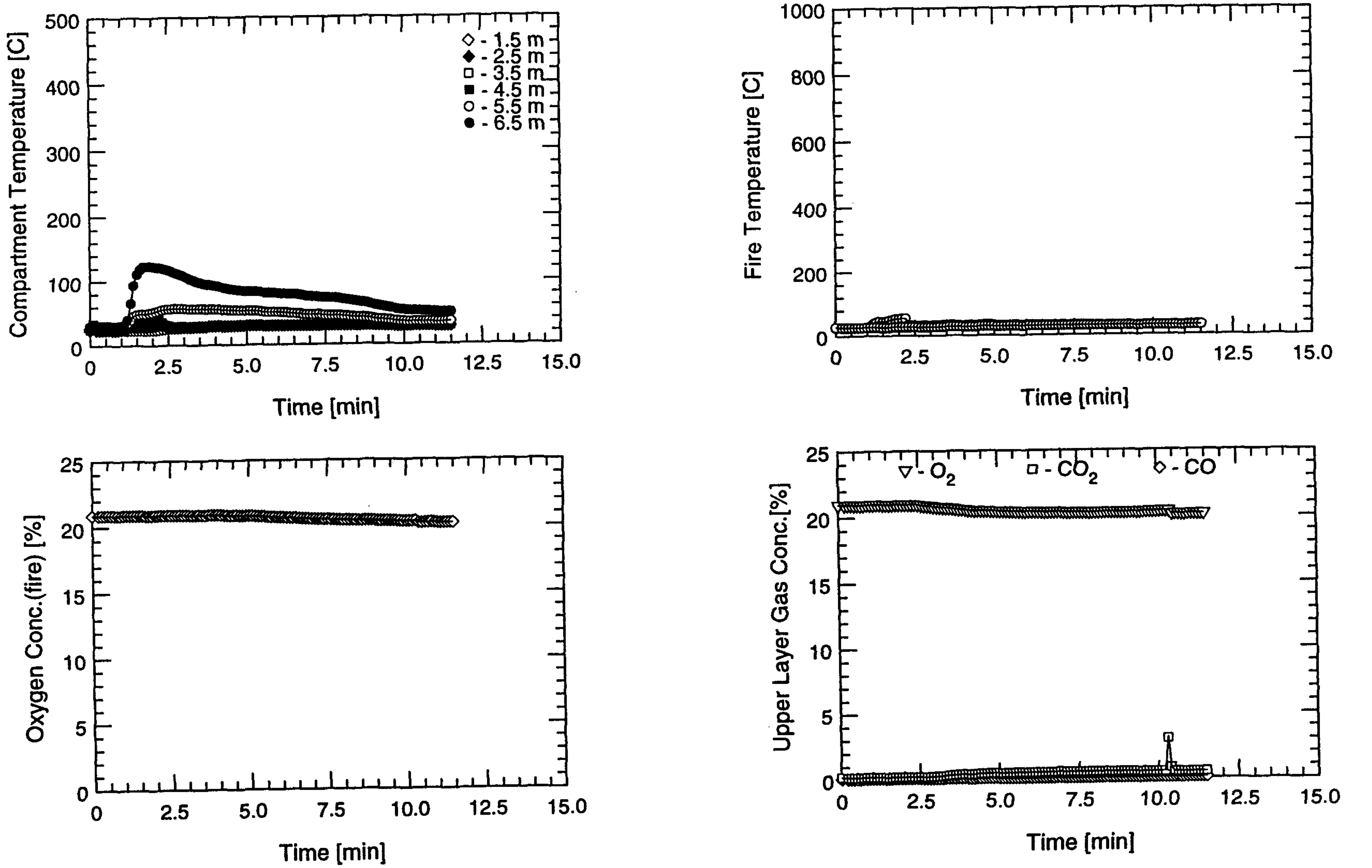


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #3

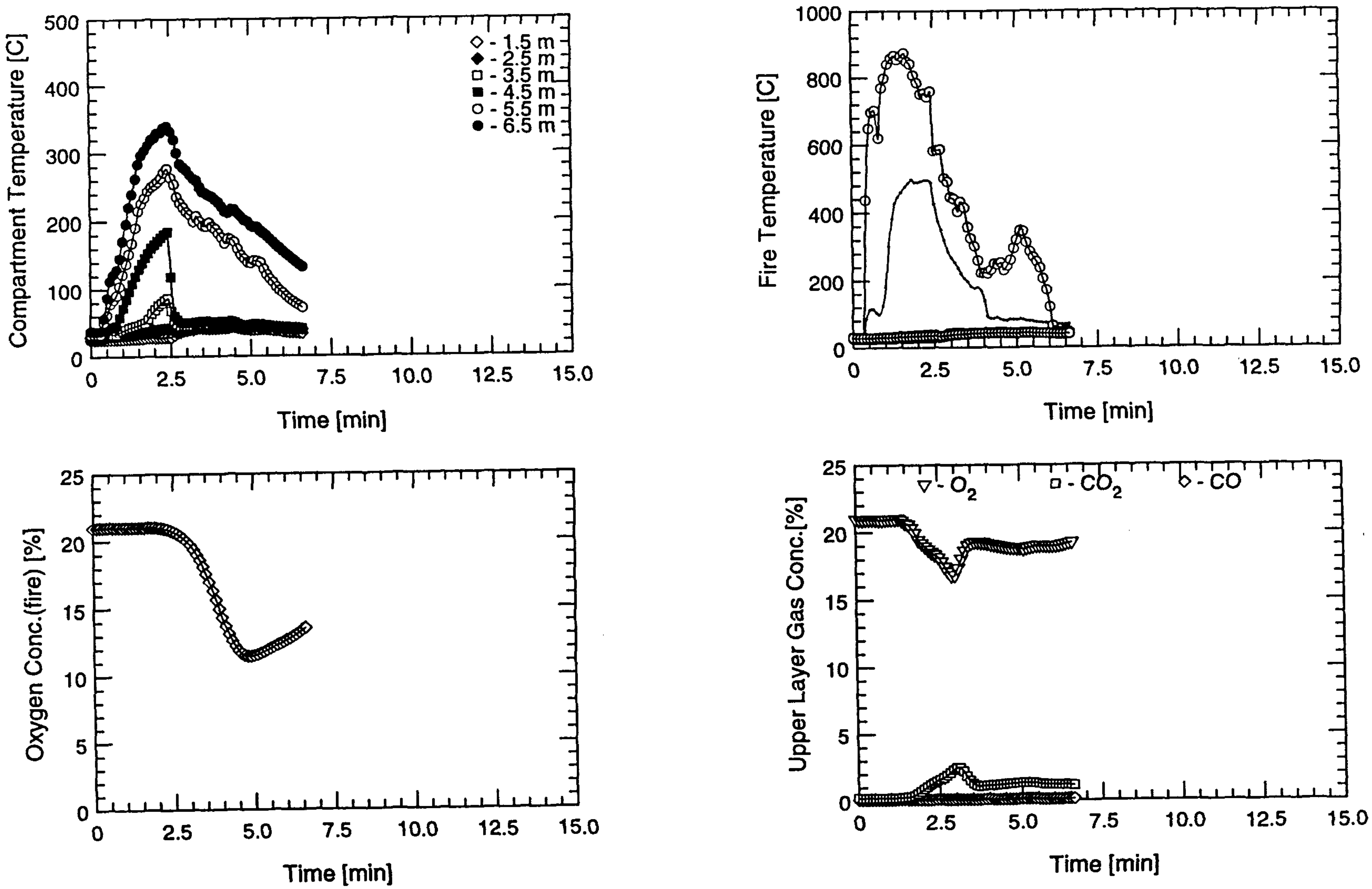

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #4



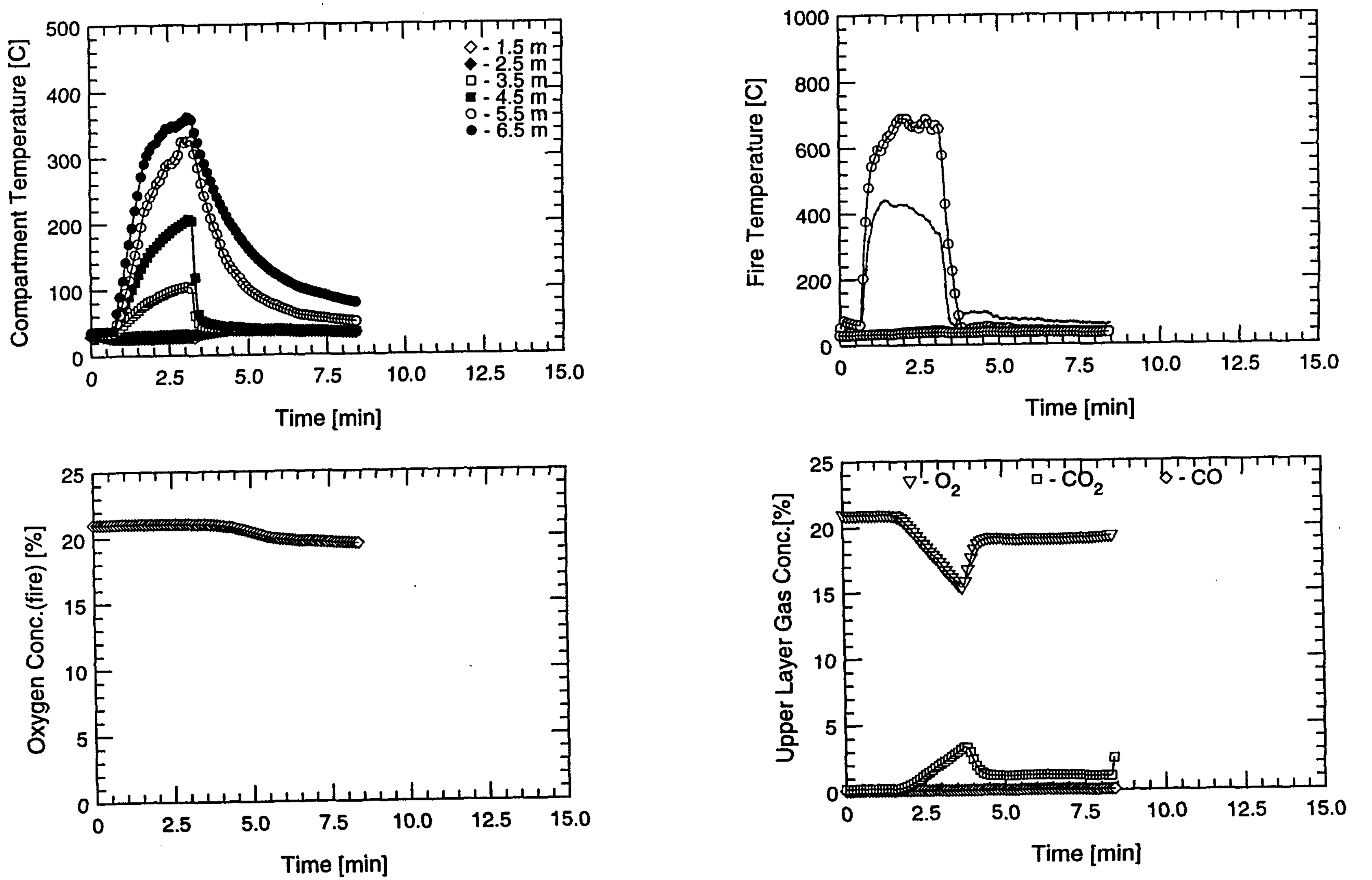
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #5



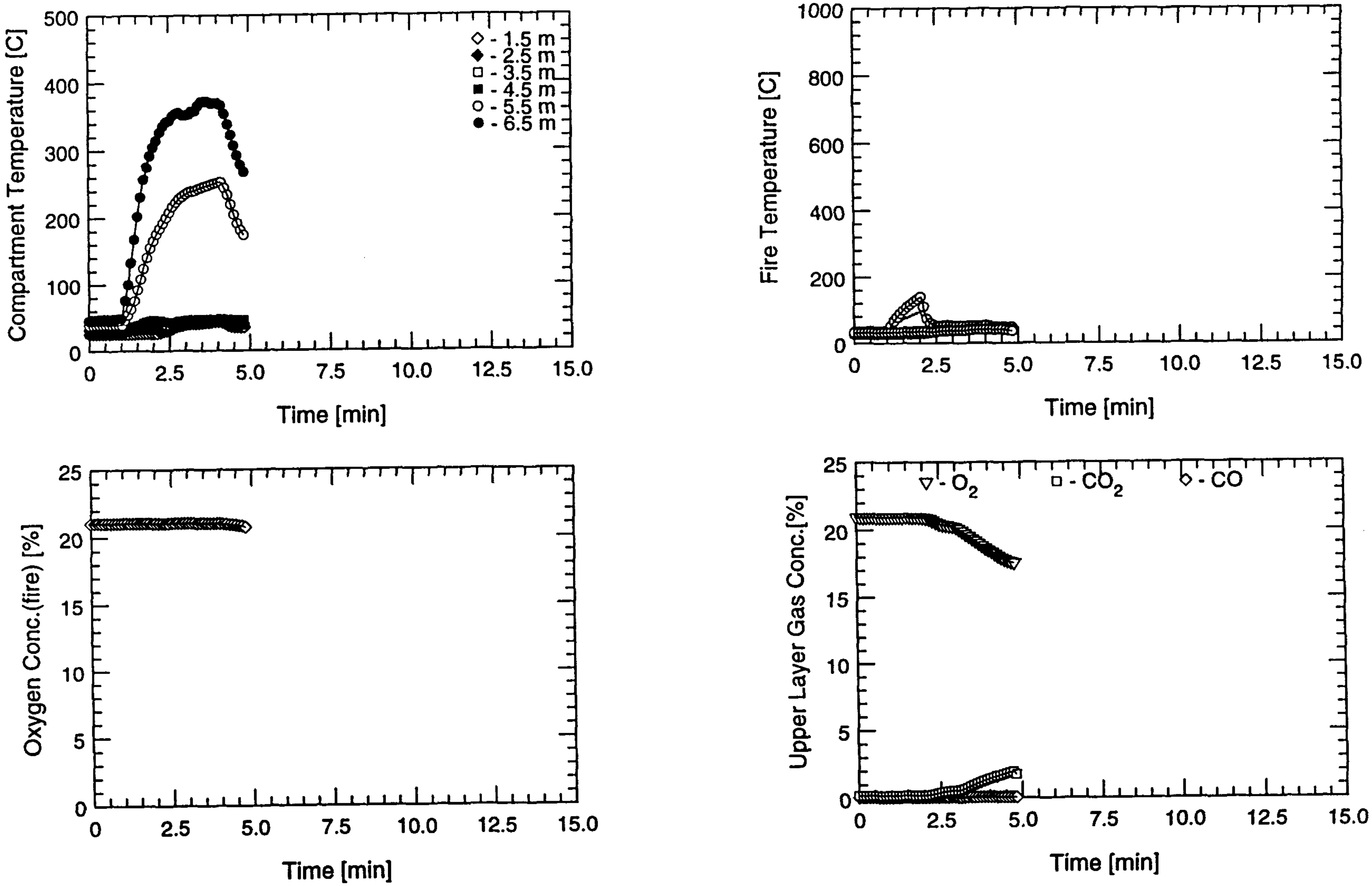
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #6

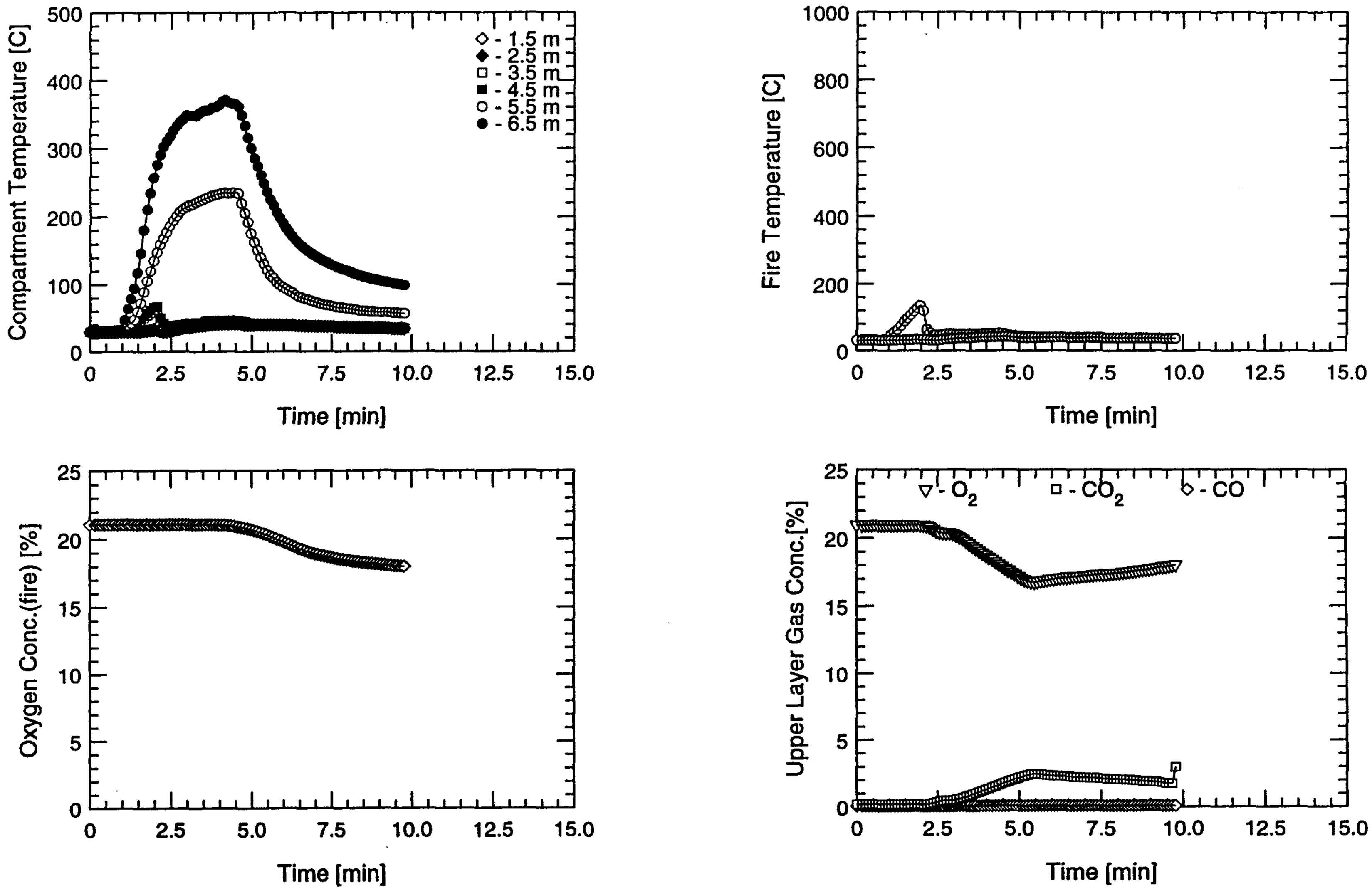


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

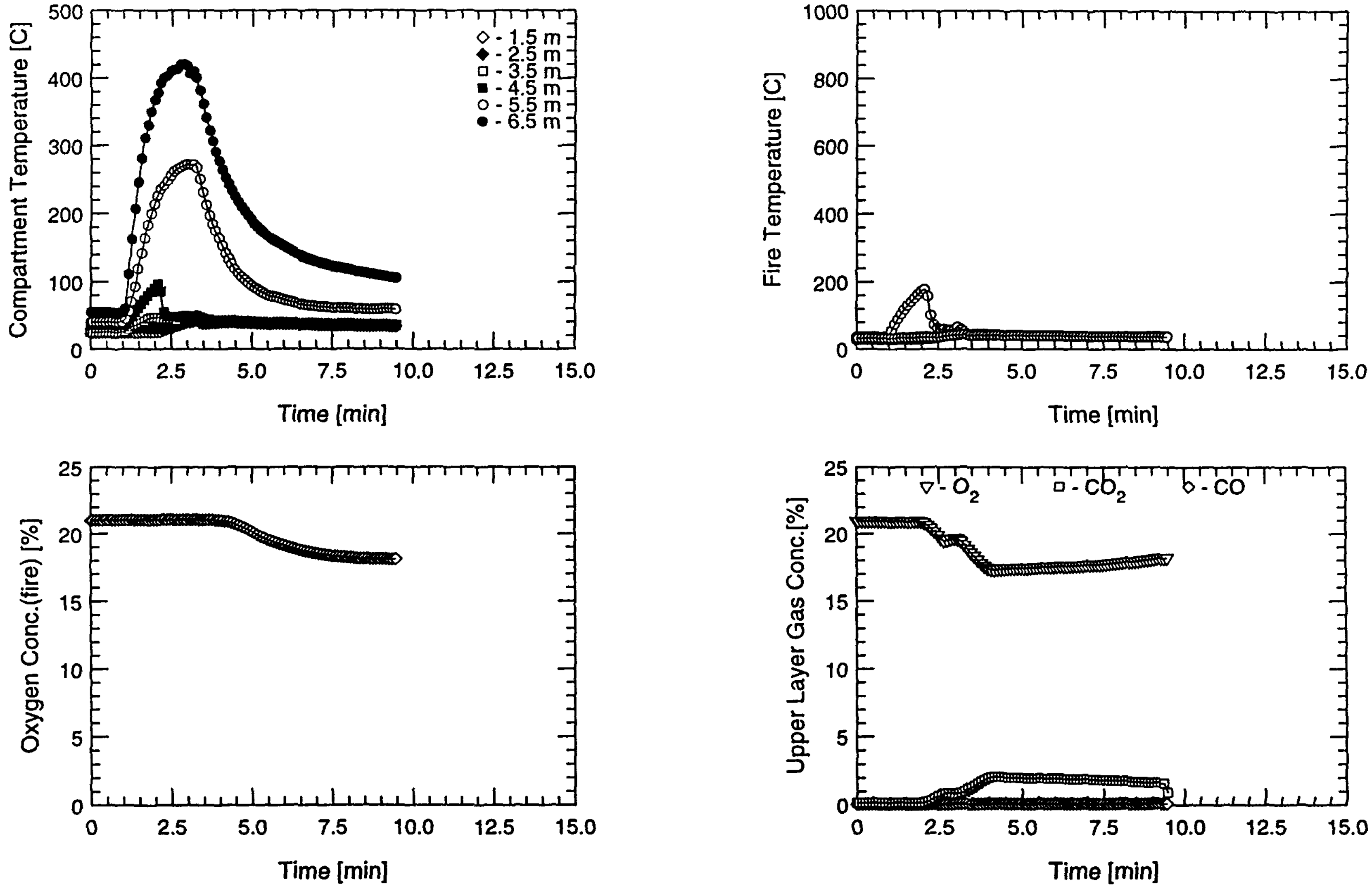
Test #7


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #8

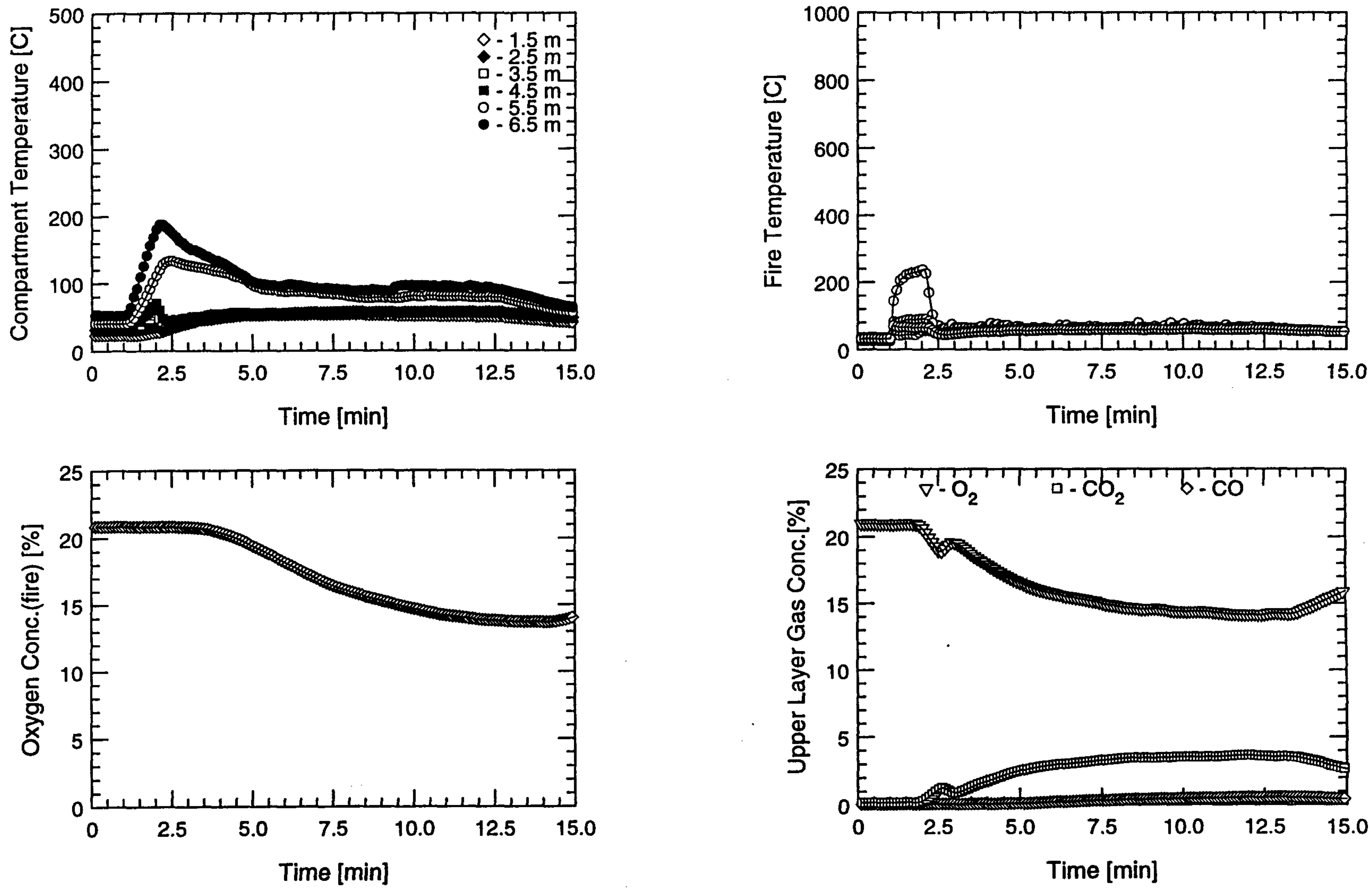

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #9



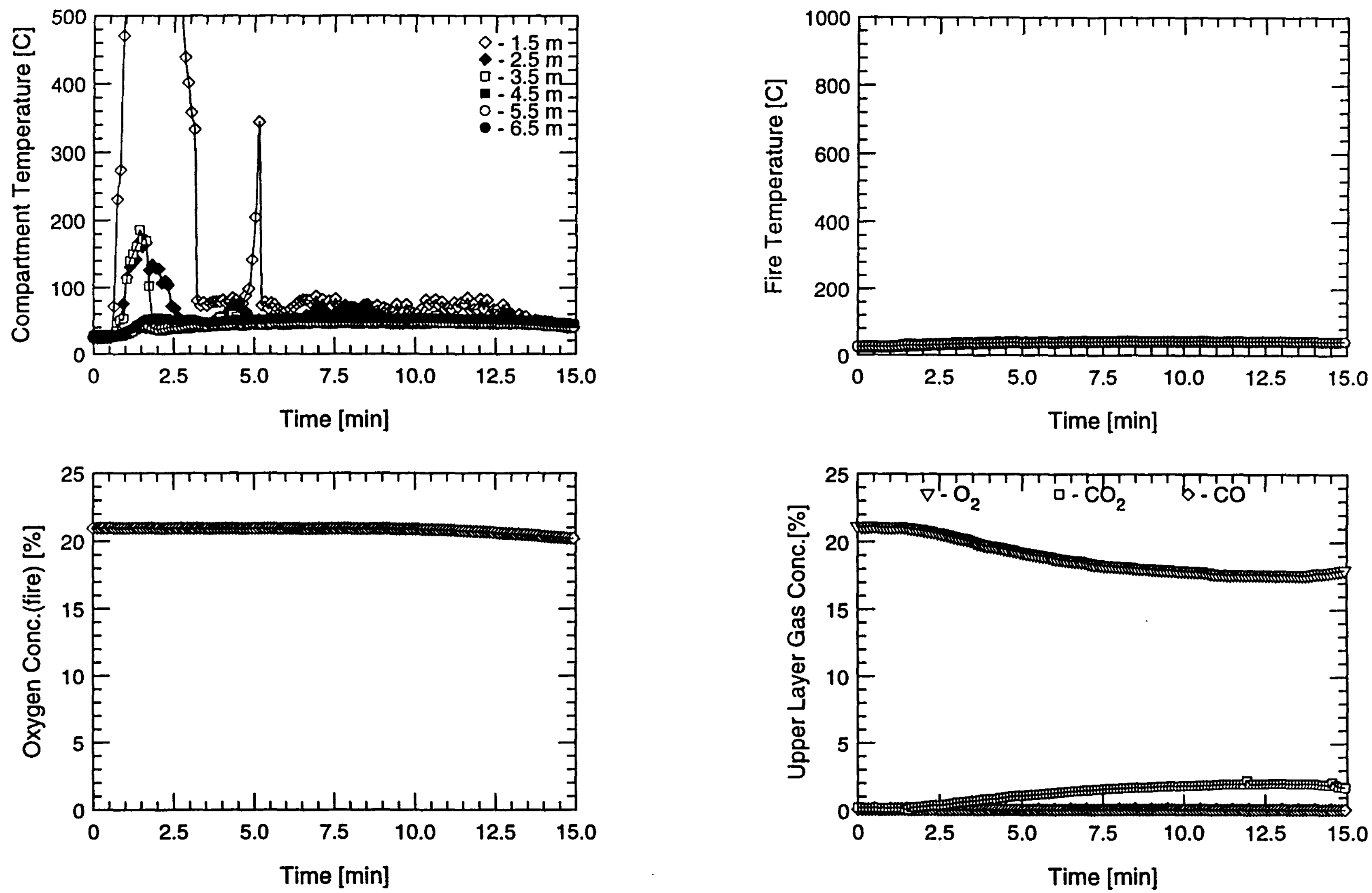
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #10

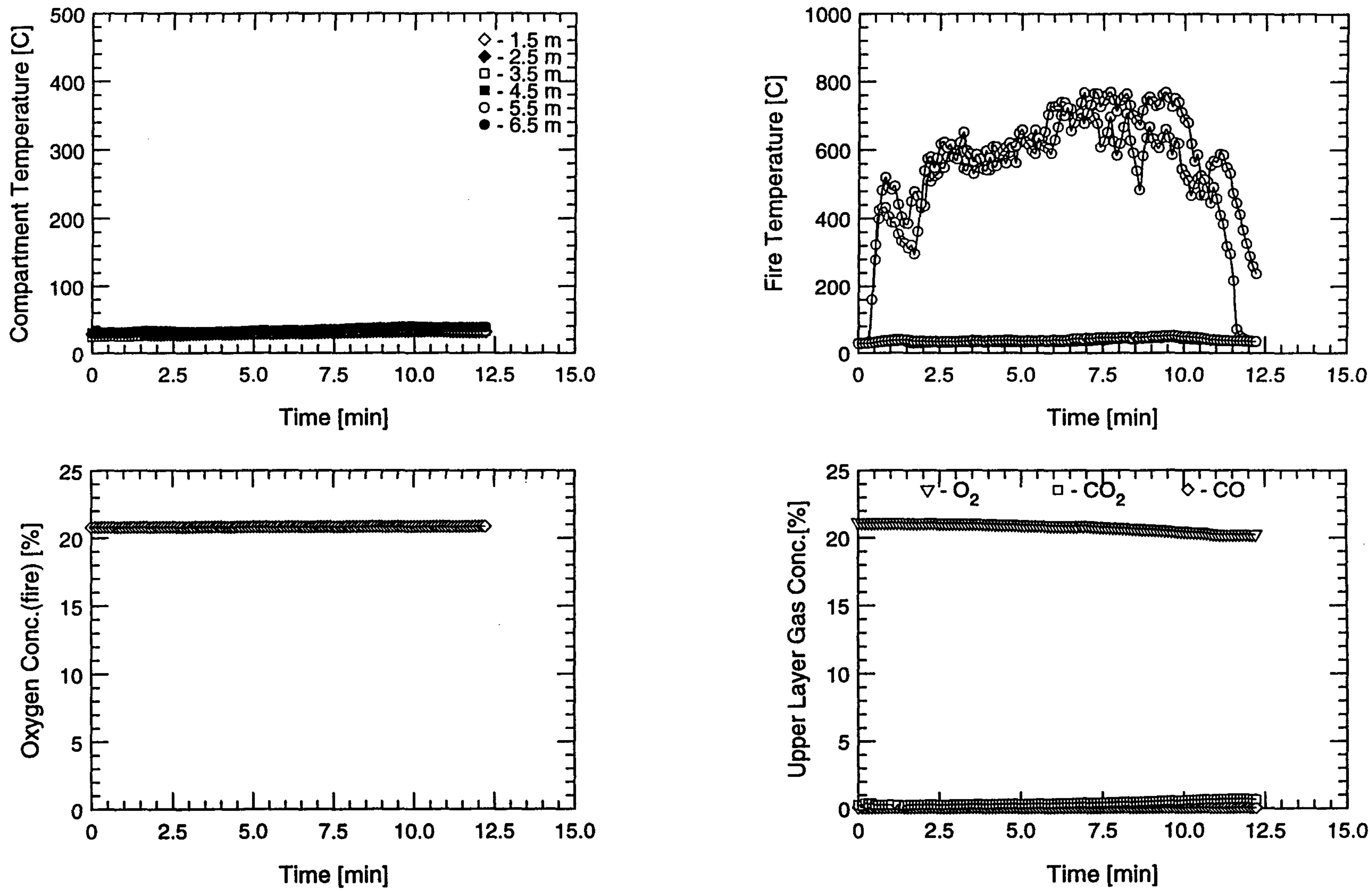


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0 2.5 5.0 7.5 10.0 12.5 15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
0 2.5 5.0 7.5 10.0 12.5 15.0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
0 2.5 5.0 7.5 10.0 12.5 15.0
Time [min]
Upper Layer Gas Conc.[%]
25
20
15
10
5
0
▽ - O_2
□ - CO_2
◇ - CO
0 2.5 5.0 7.5 10.0 12.5 15.0
Time [min]

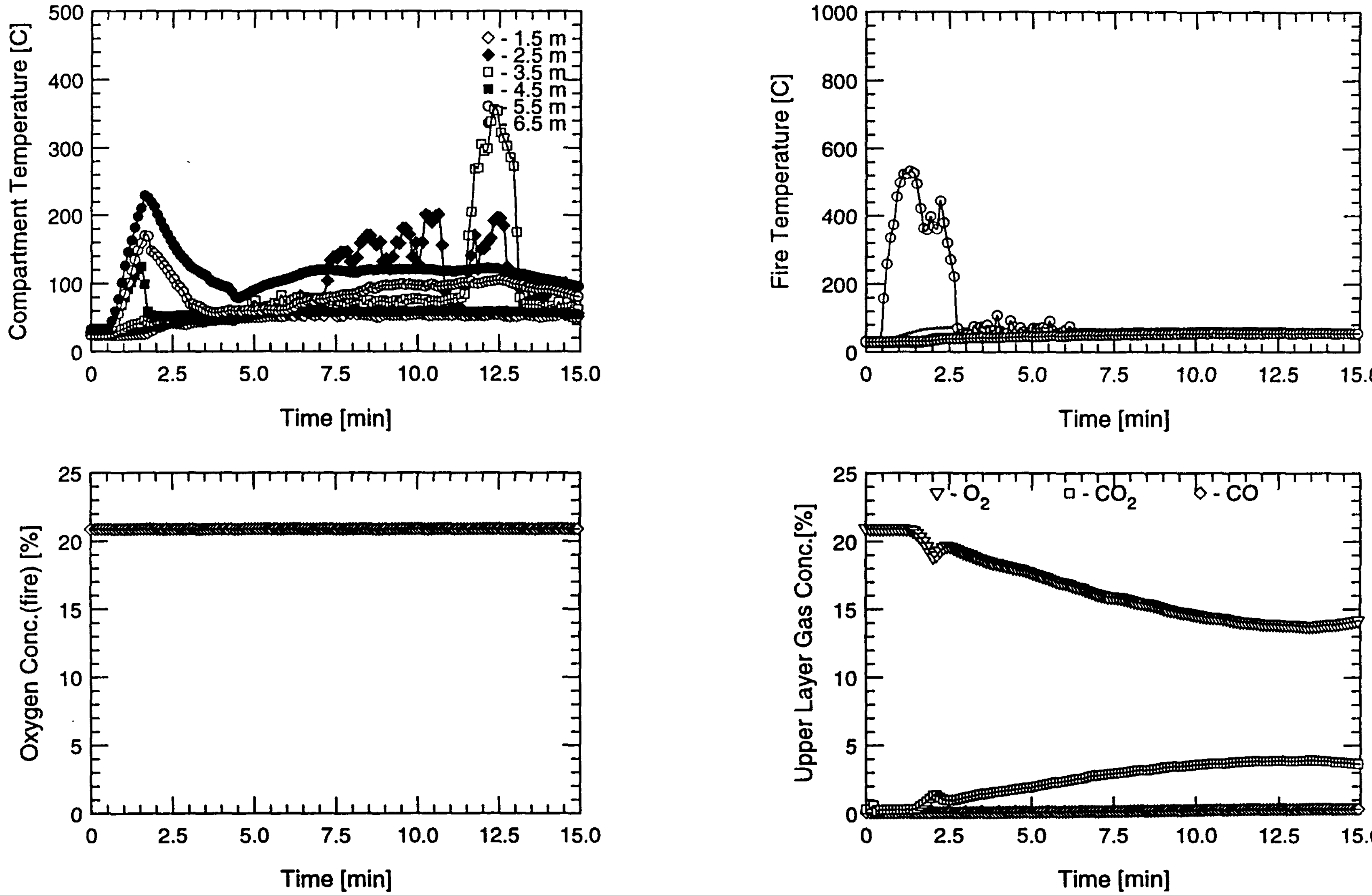
Test #11


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #12

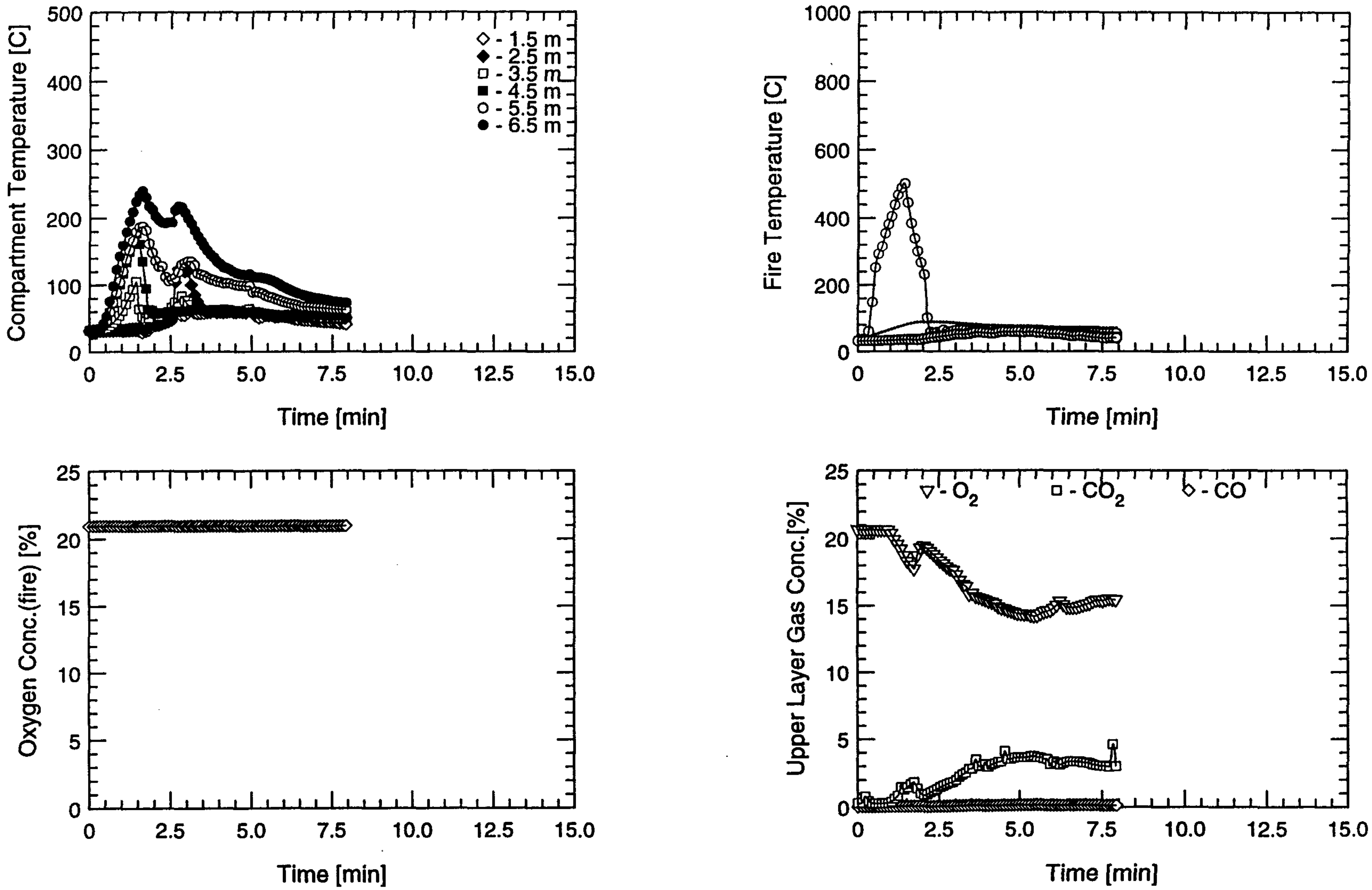

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #13

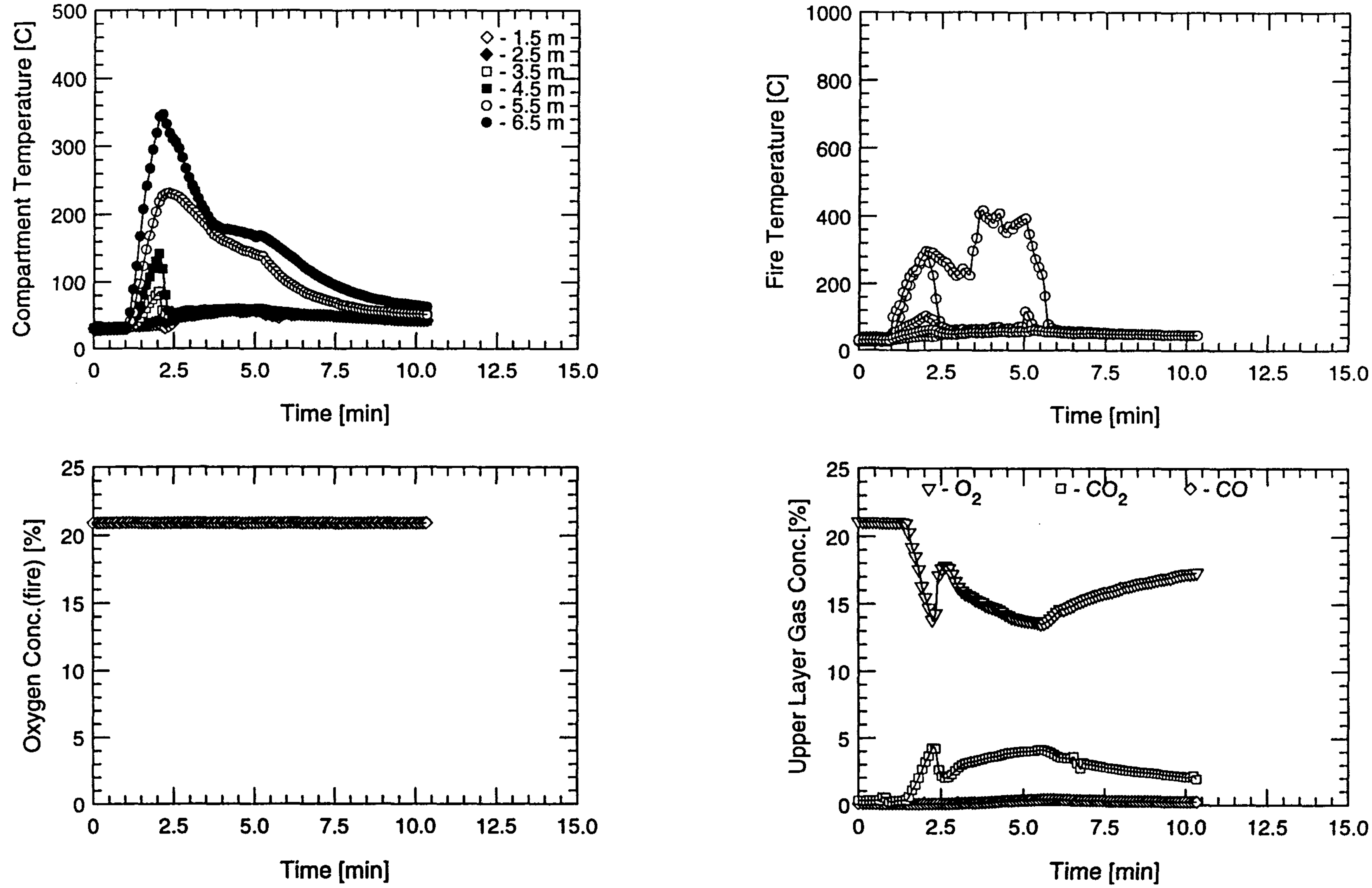


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #14

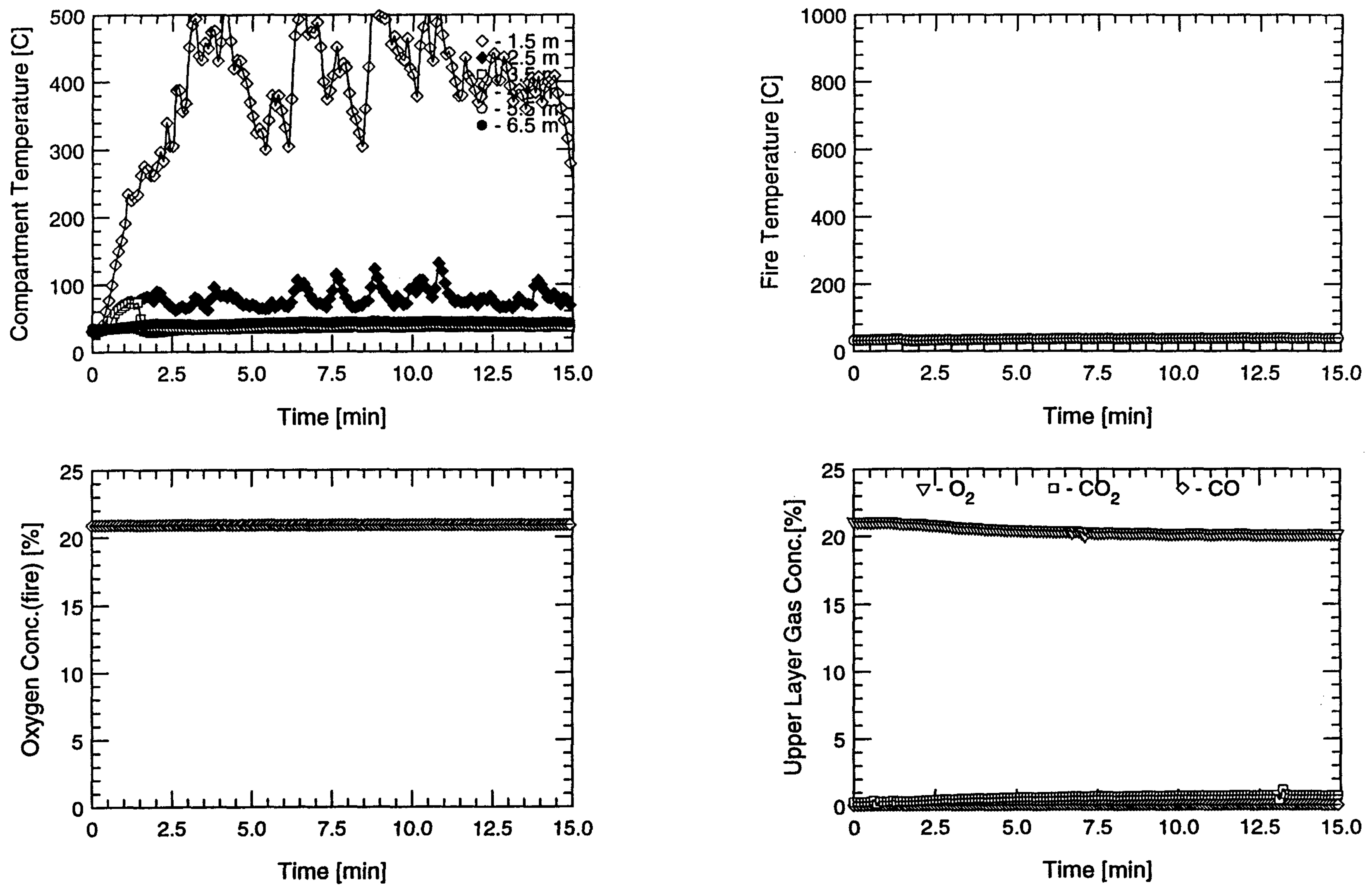

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #15

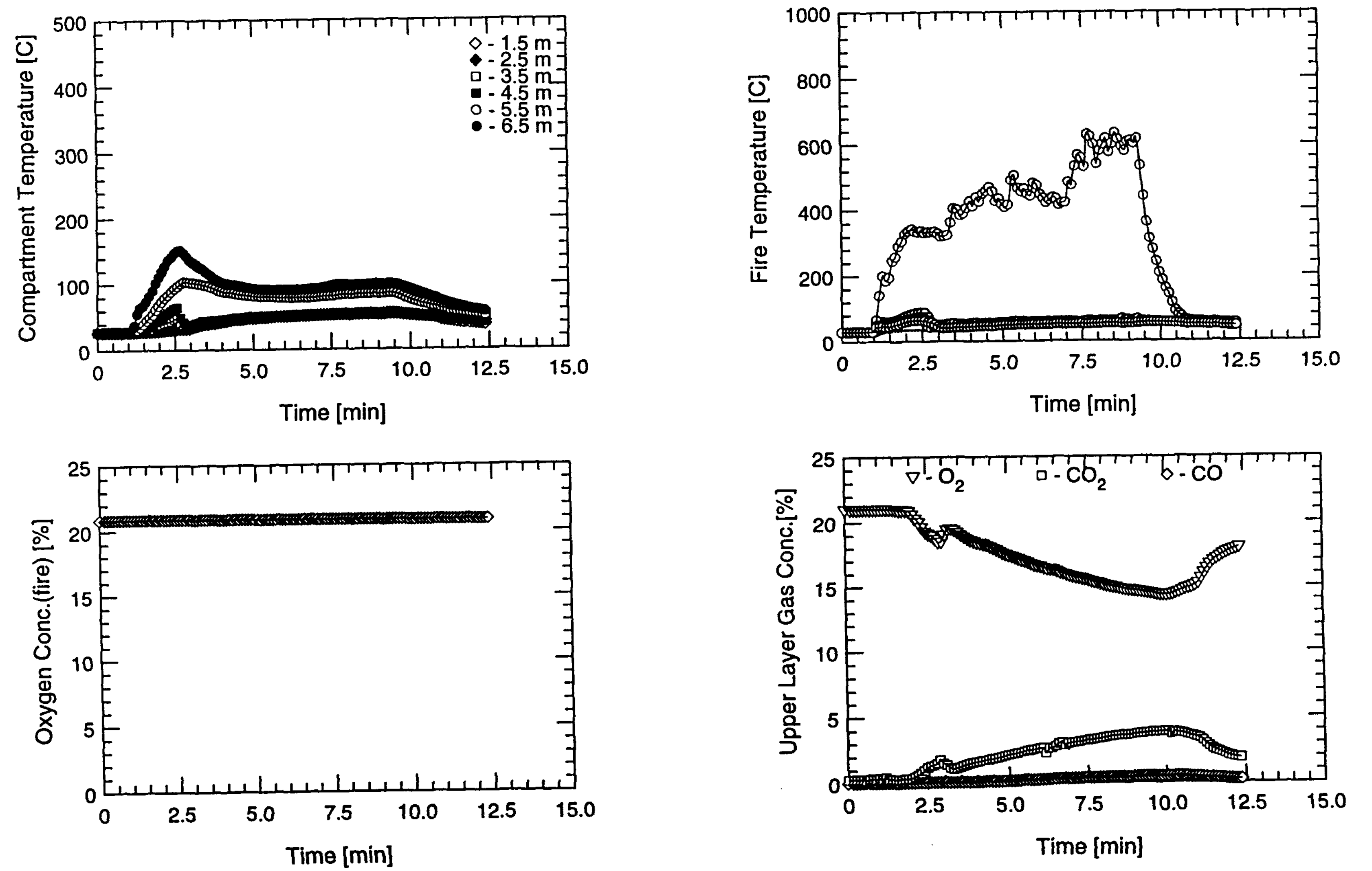


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #16

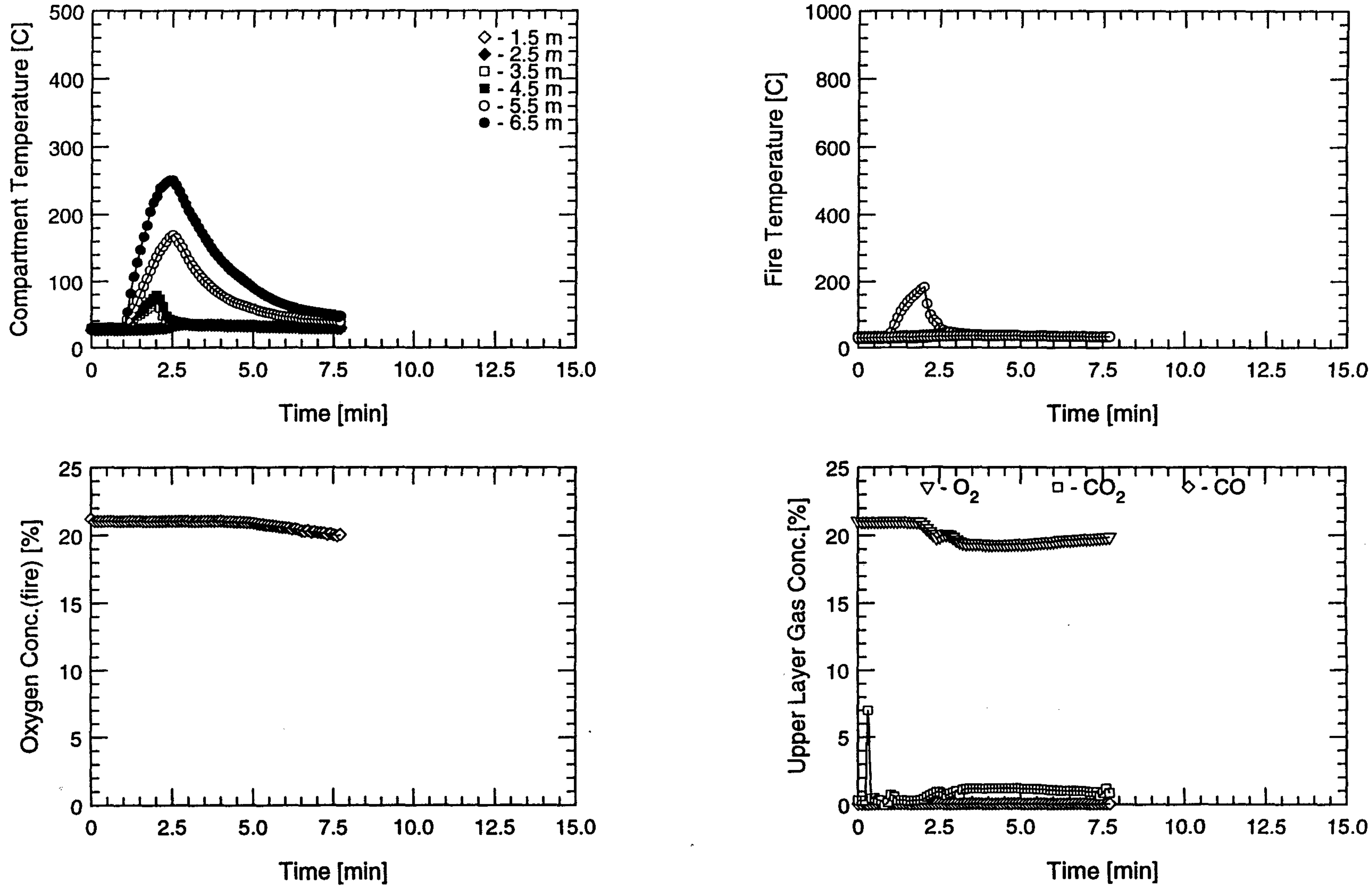

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
- 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #17

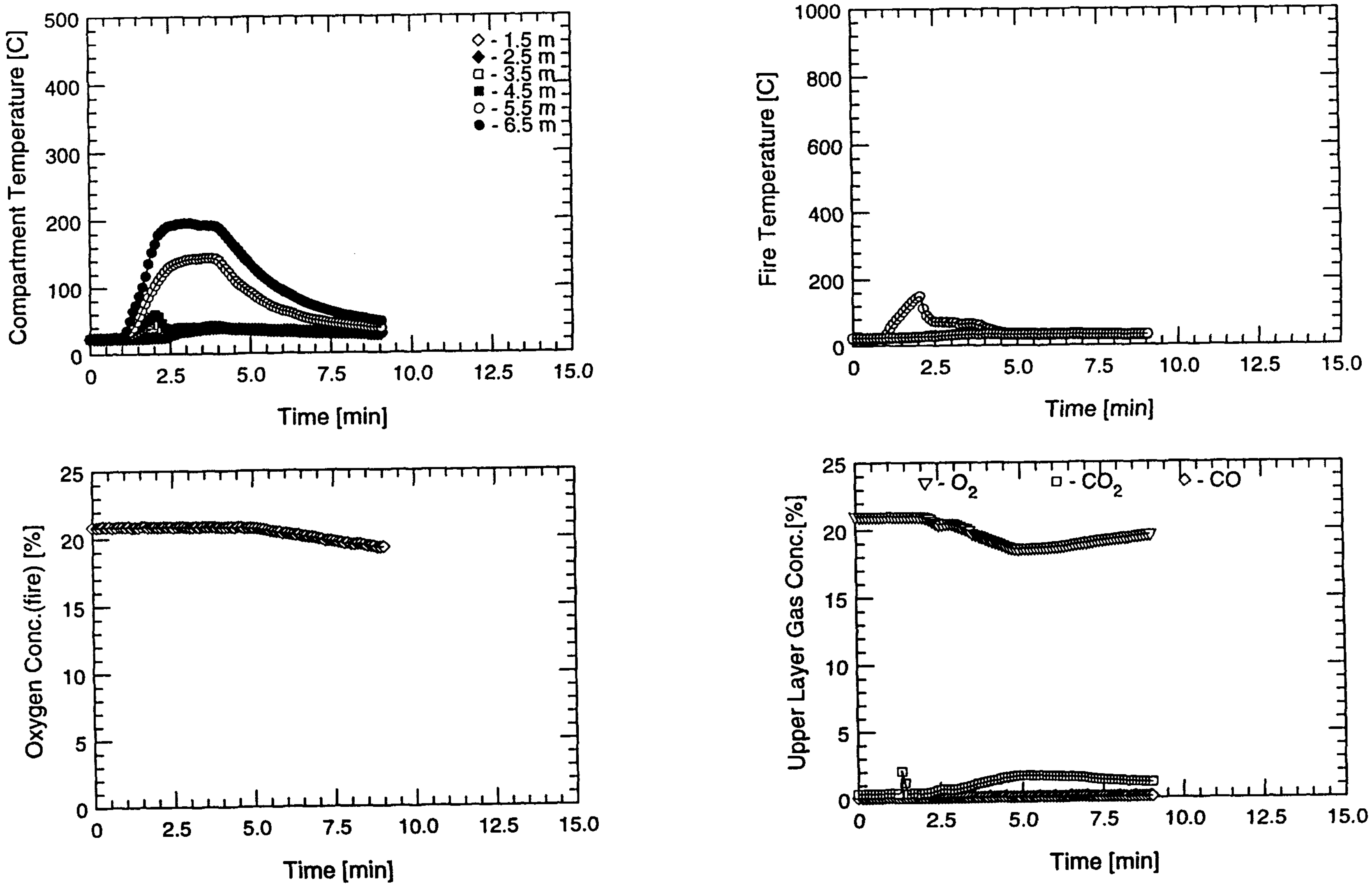


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #18

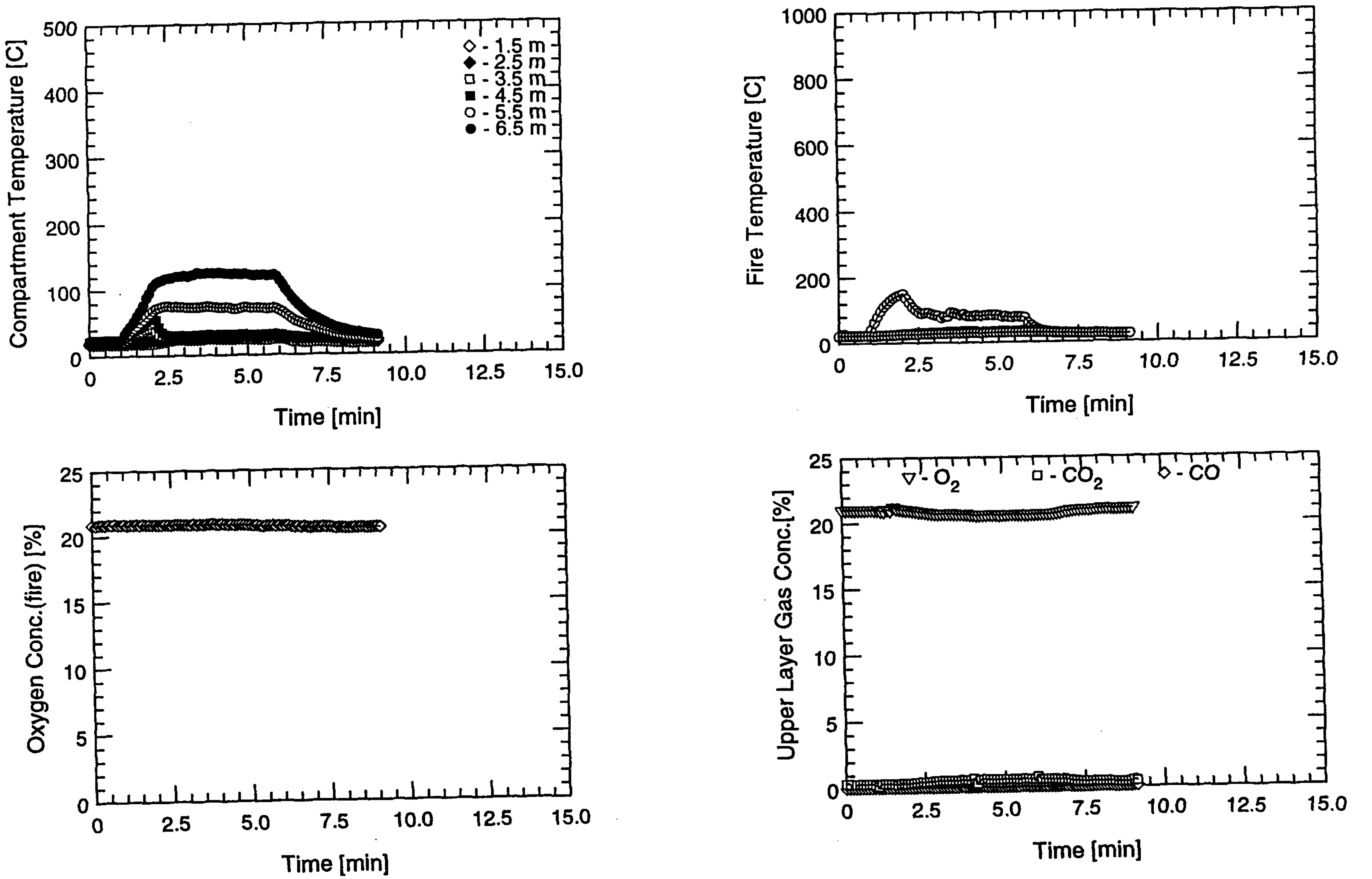

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O2
□ - CO2
◇ - CO

Test #19



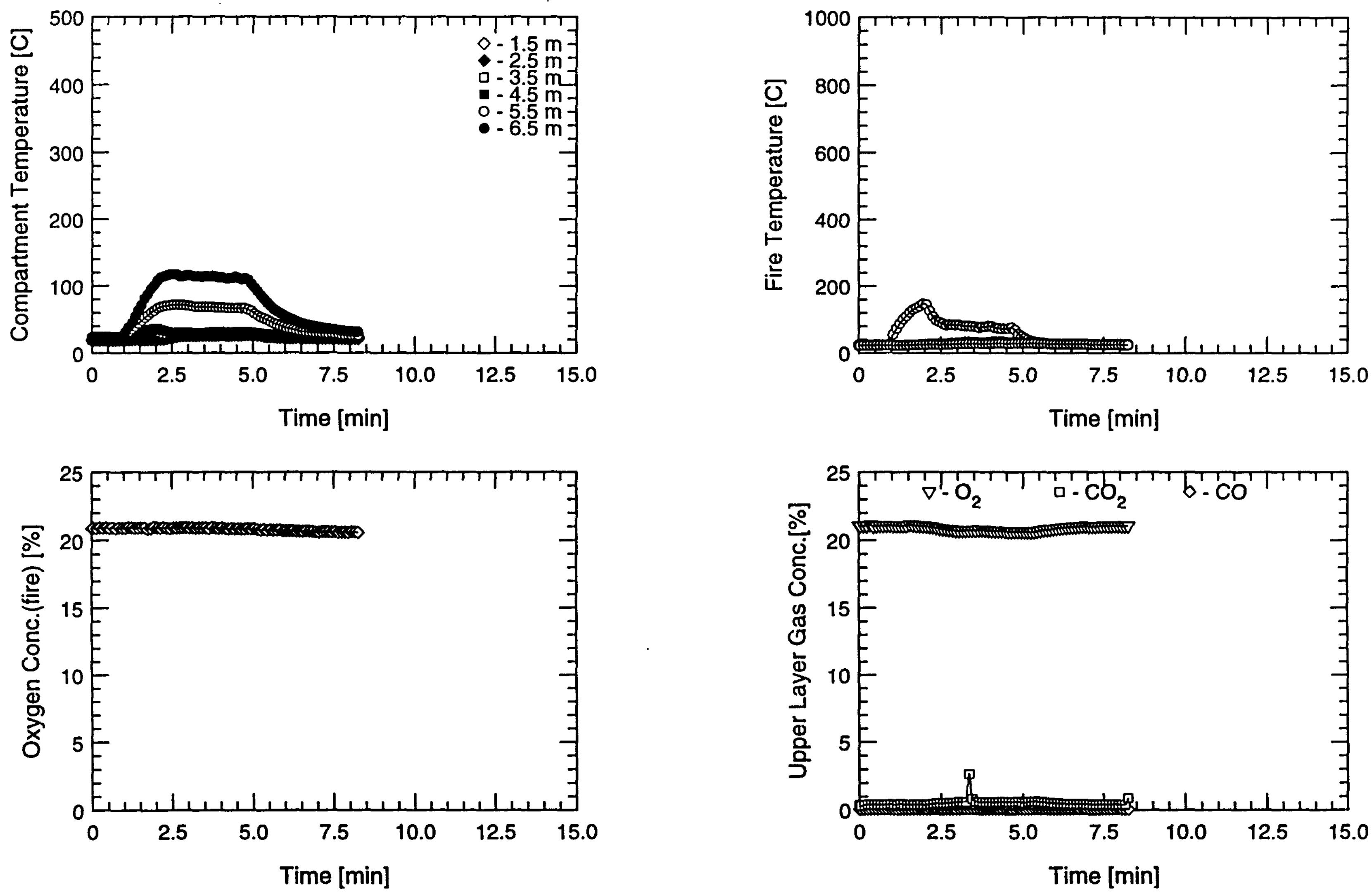
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #20



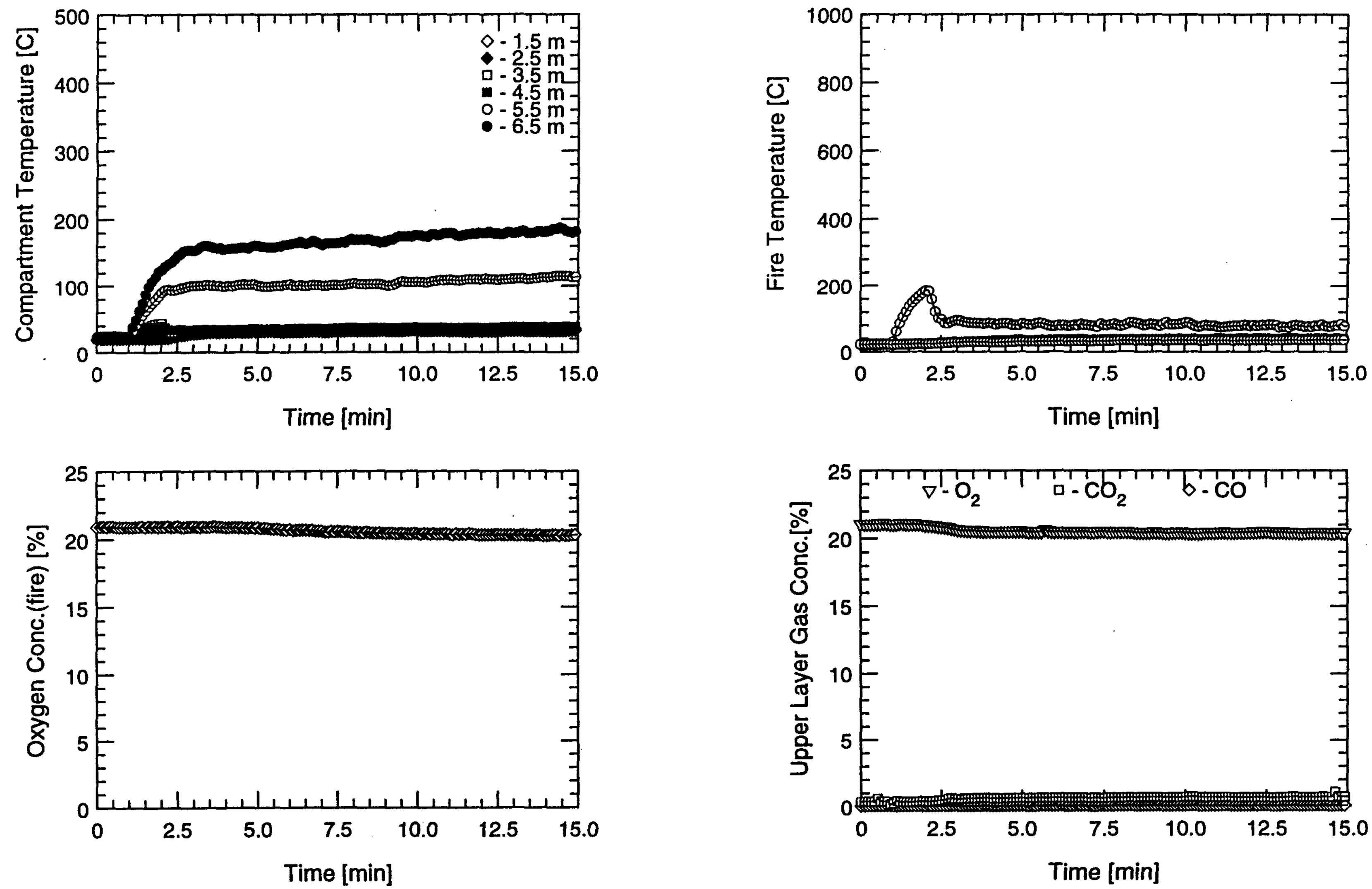
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #21

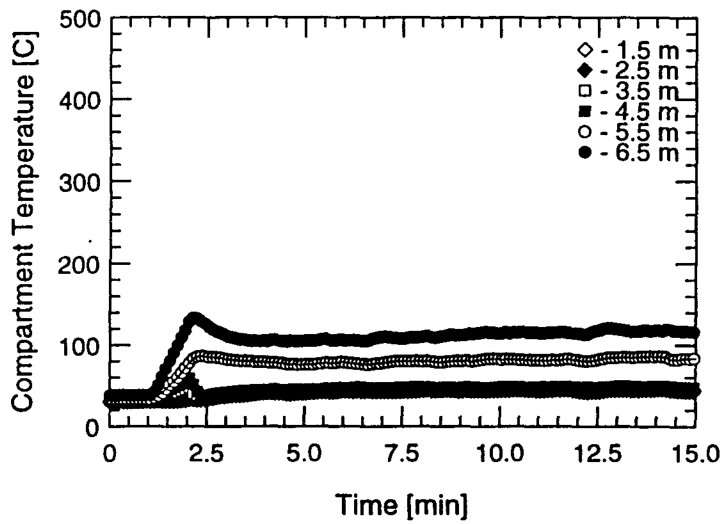


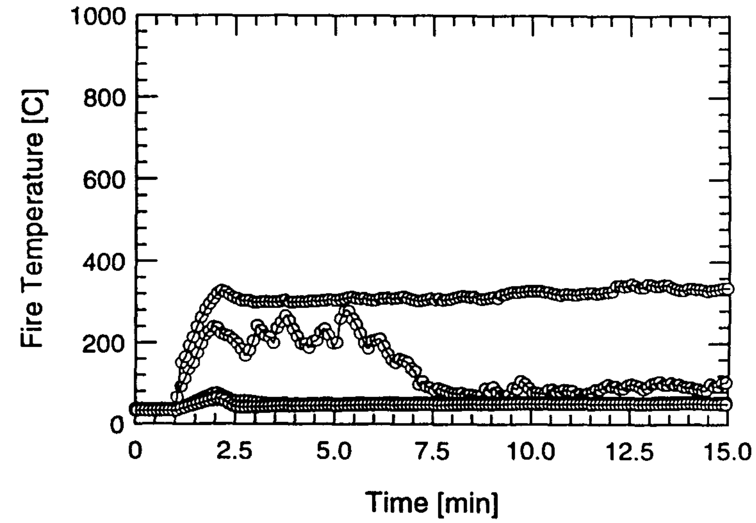
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

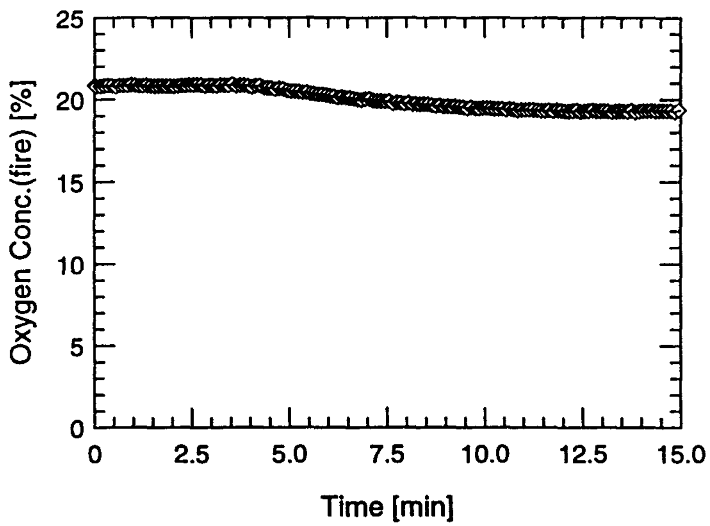
Test #22

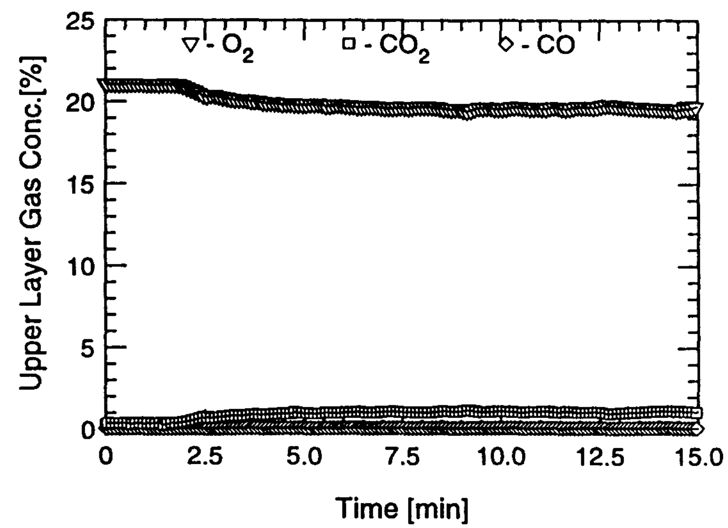

Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0 2.5 5.0 7.5 10.0 12.5 15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
0 2.5 5.0 7.5 10.0 12.5 15.0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
0 2.5 5.0 7.5 10.0 12.5 15.0
Time [min]
Upper Layer Gas Conc.[%]
25
20
15
10
5
0
▽ - O2
□ - CO2
◇ - CO
0 2.5 5.0 7.5 10.0 12.5 15.0
Time [min]

Test #23

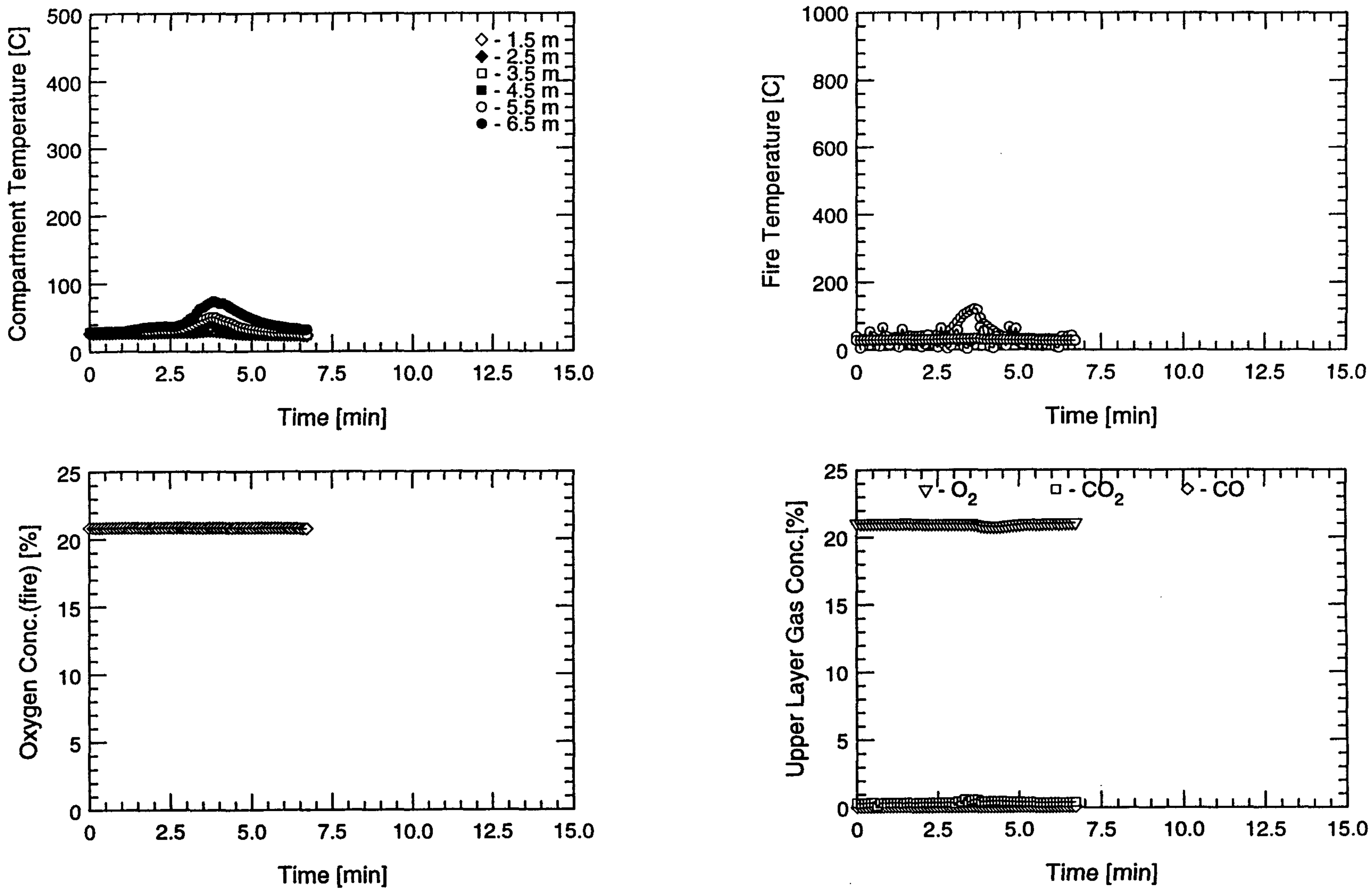

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m


Fire Temperature [C]
Time [min]

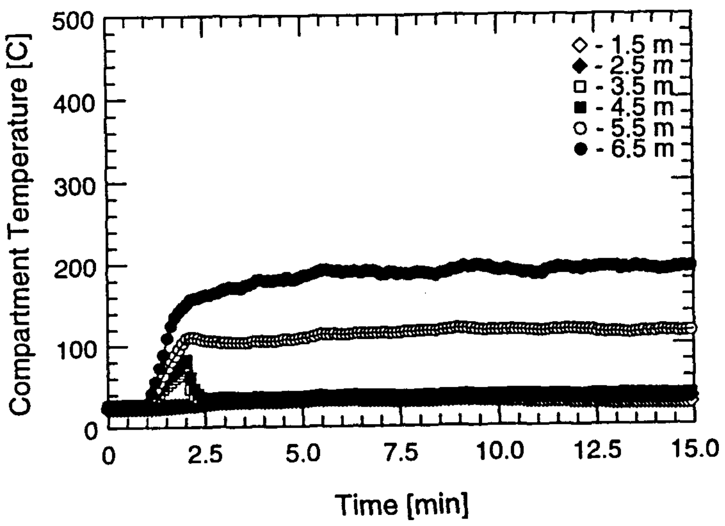

Oxygen Conc.(fire) [%]
Time [min]

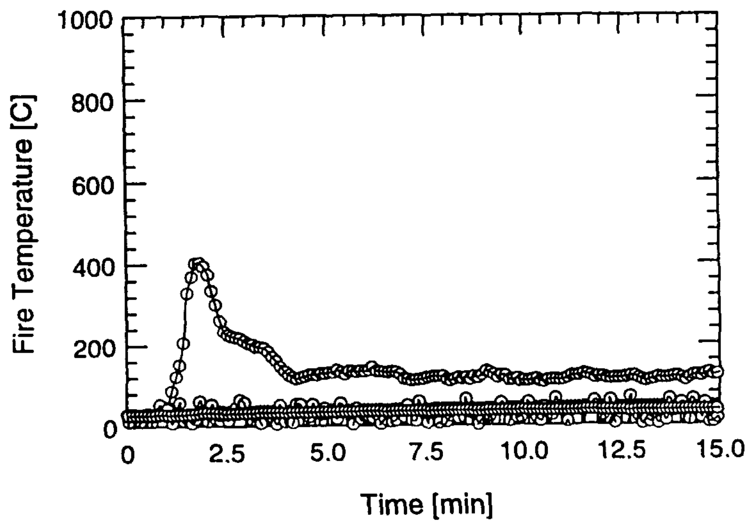

Upper Layer Gas Conc.[%]
Time [min]
▽ - O2
□ - CO2
◇ - CO

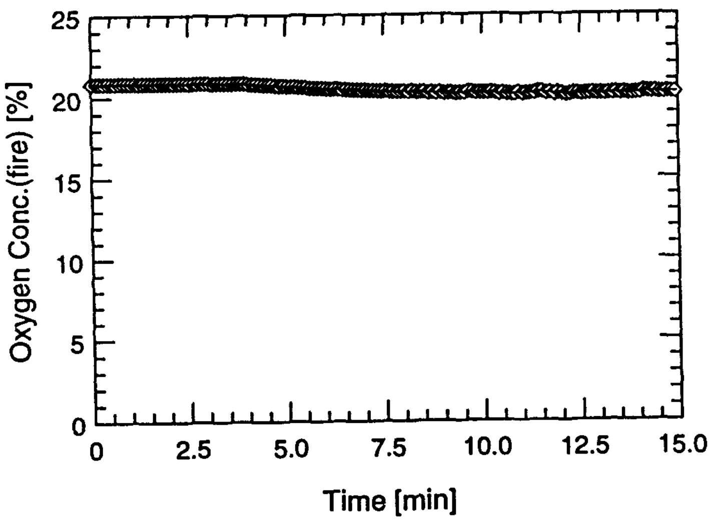
Test #24

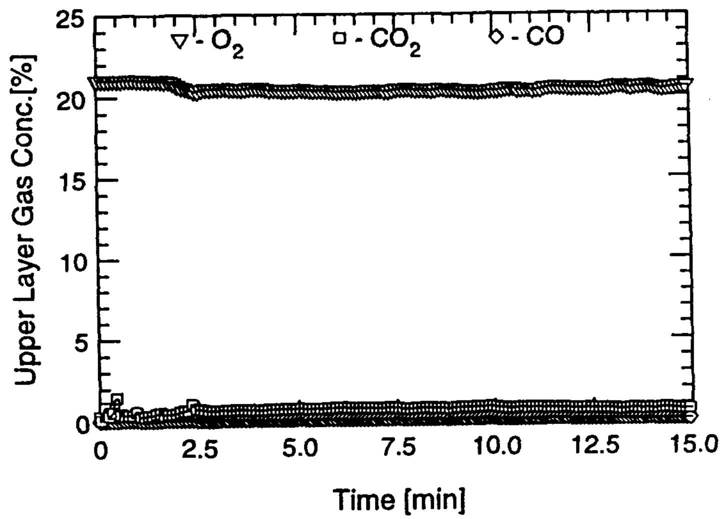

Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #25

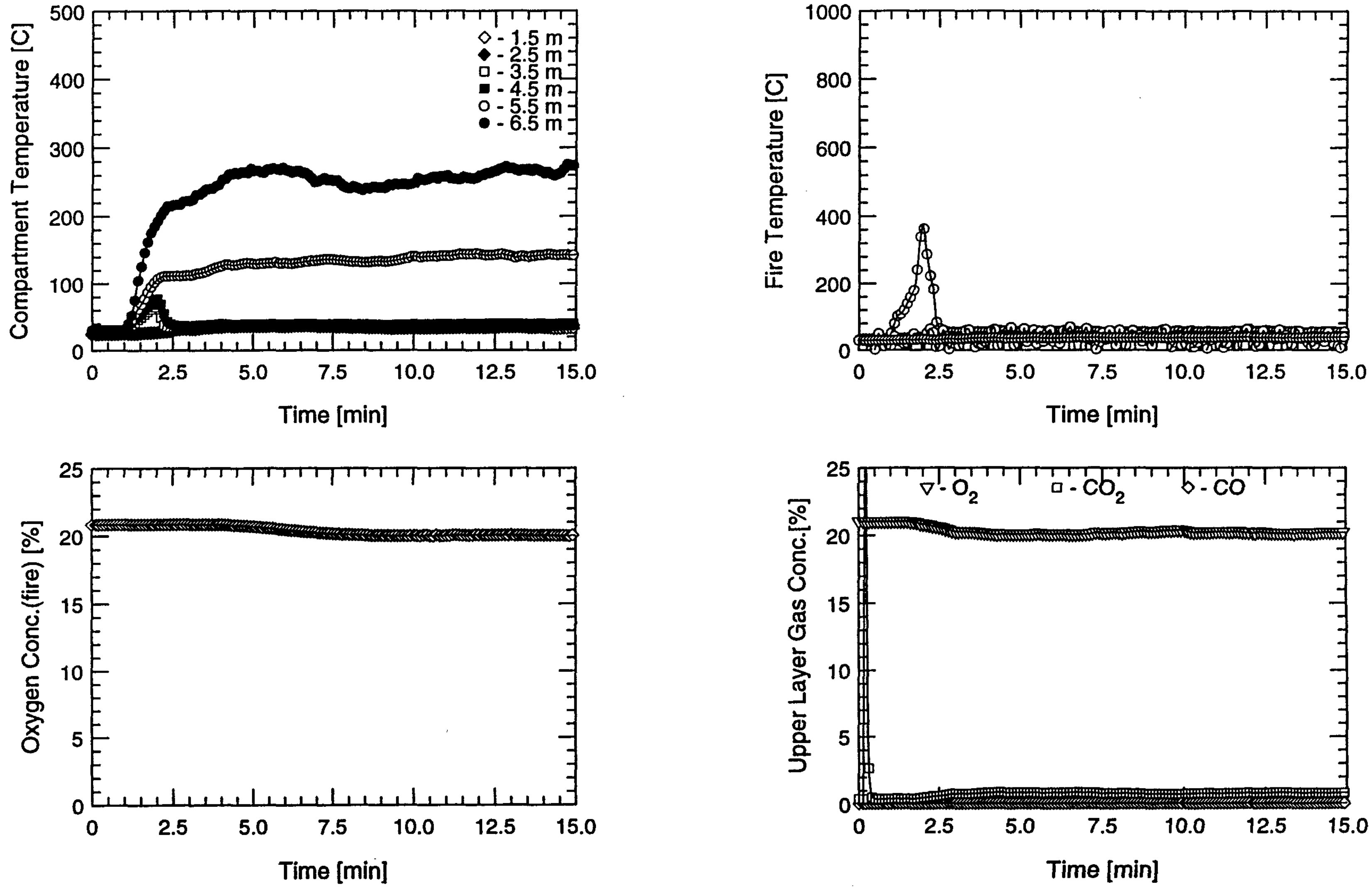

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m


Fire Temperature [C]
Time [min]

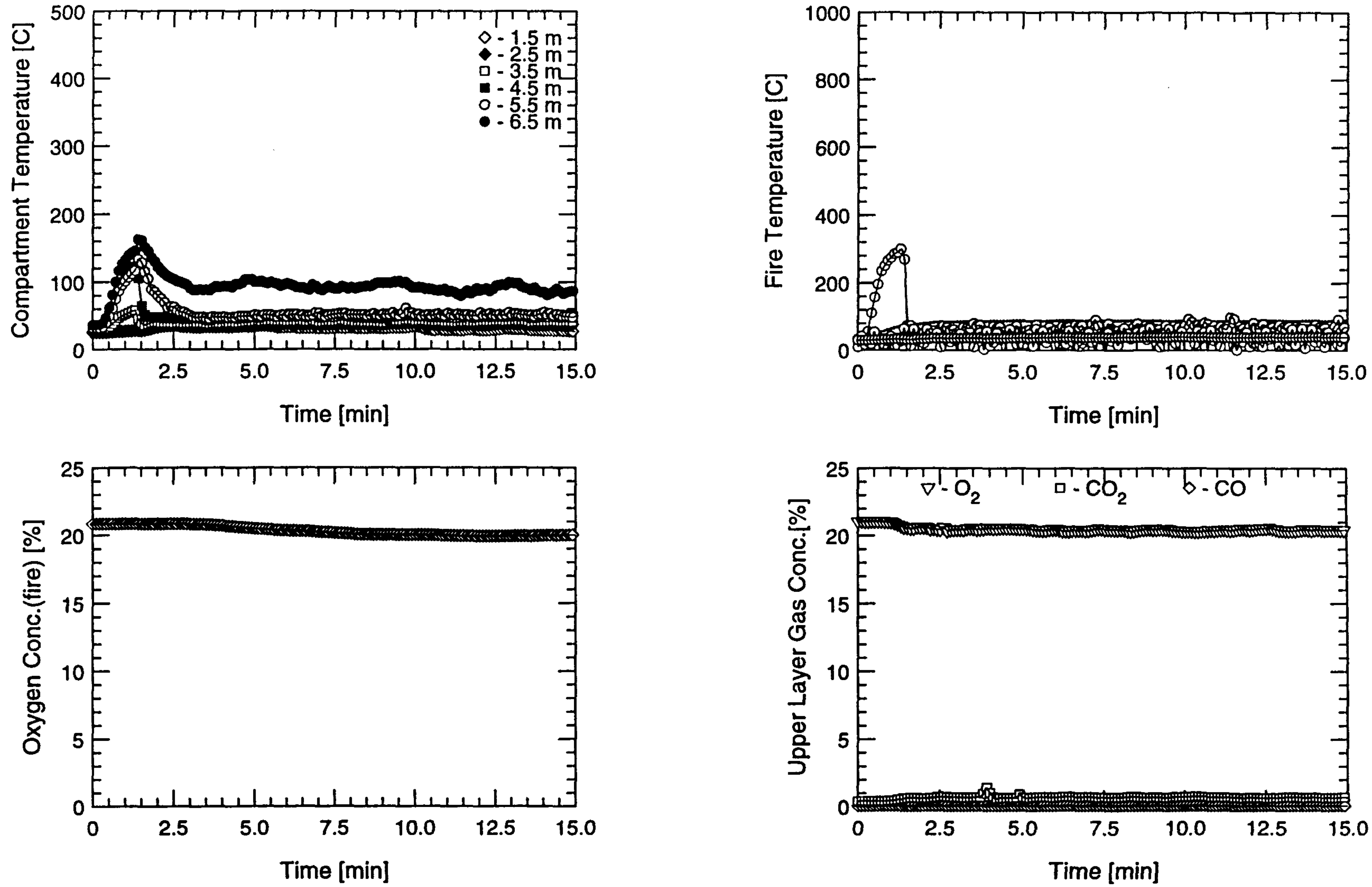

Oxygen Conc.(fire) [%]
Time [min]


Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #26

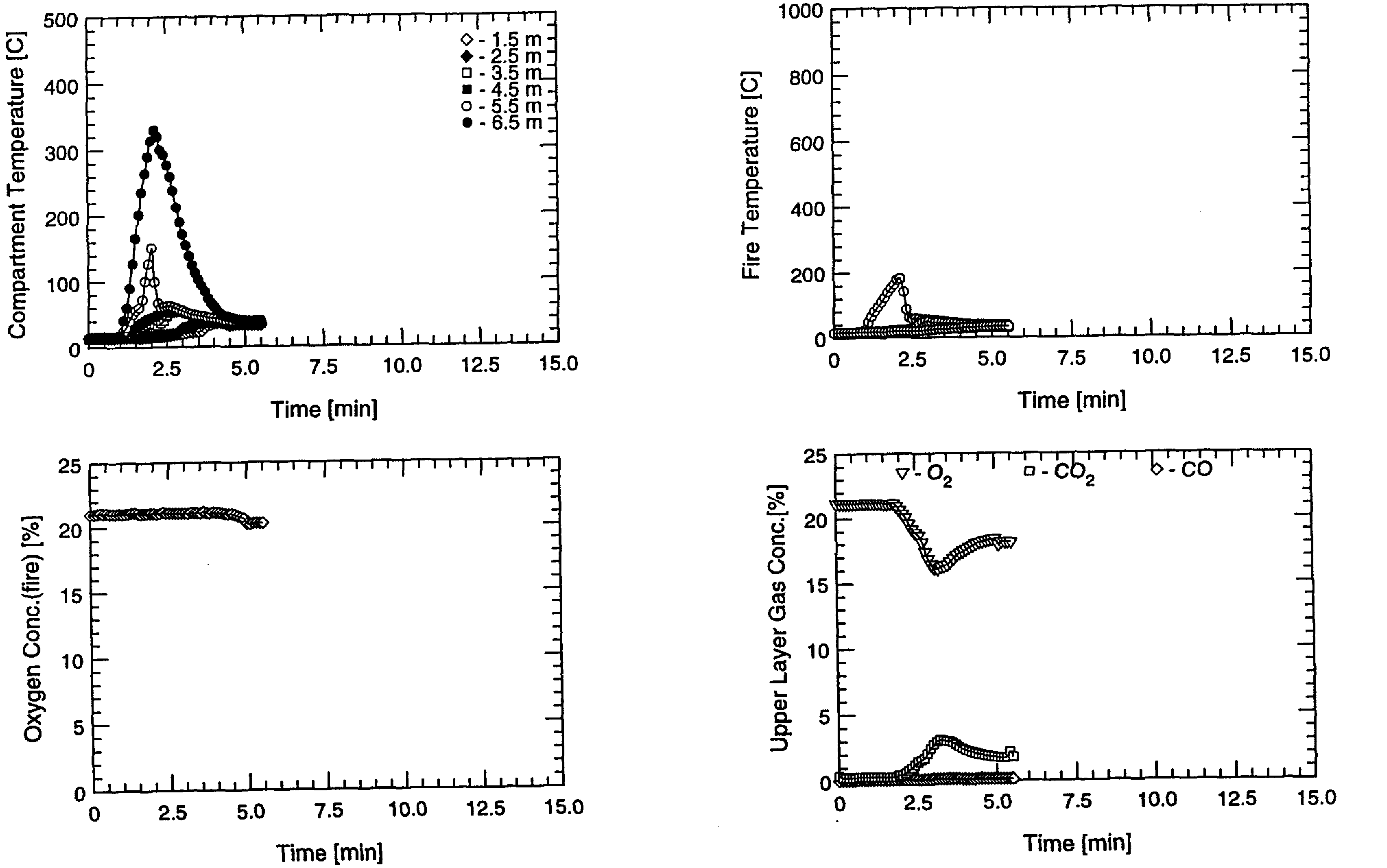

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #27

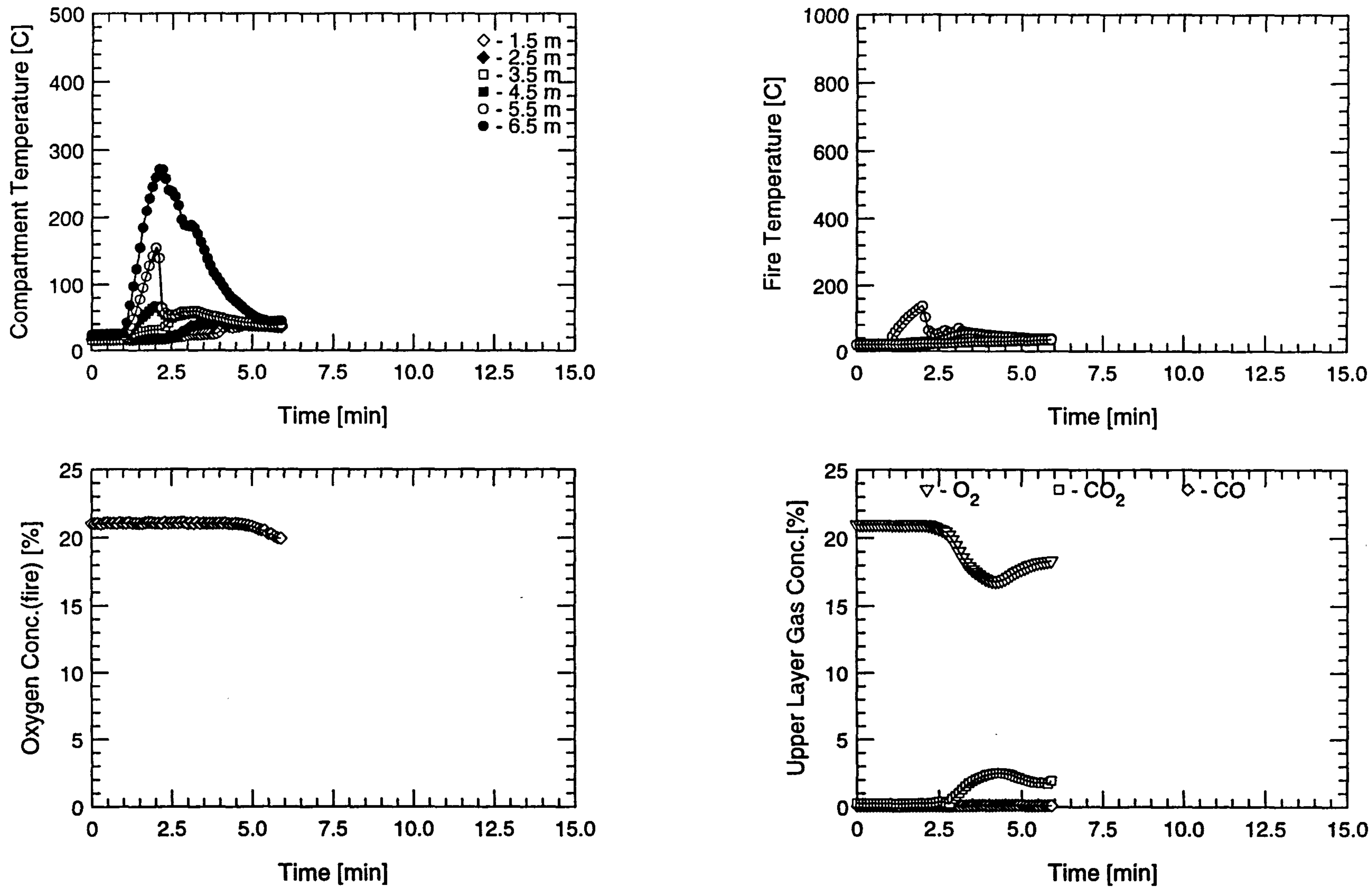


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #28

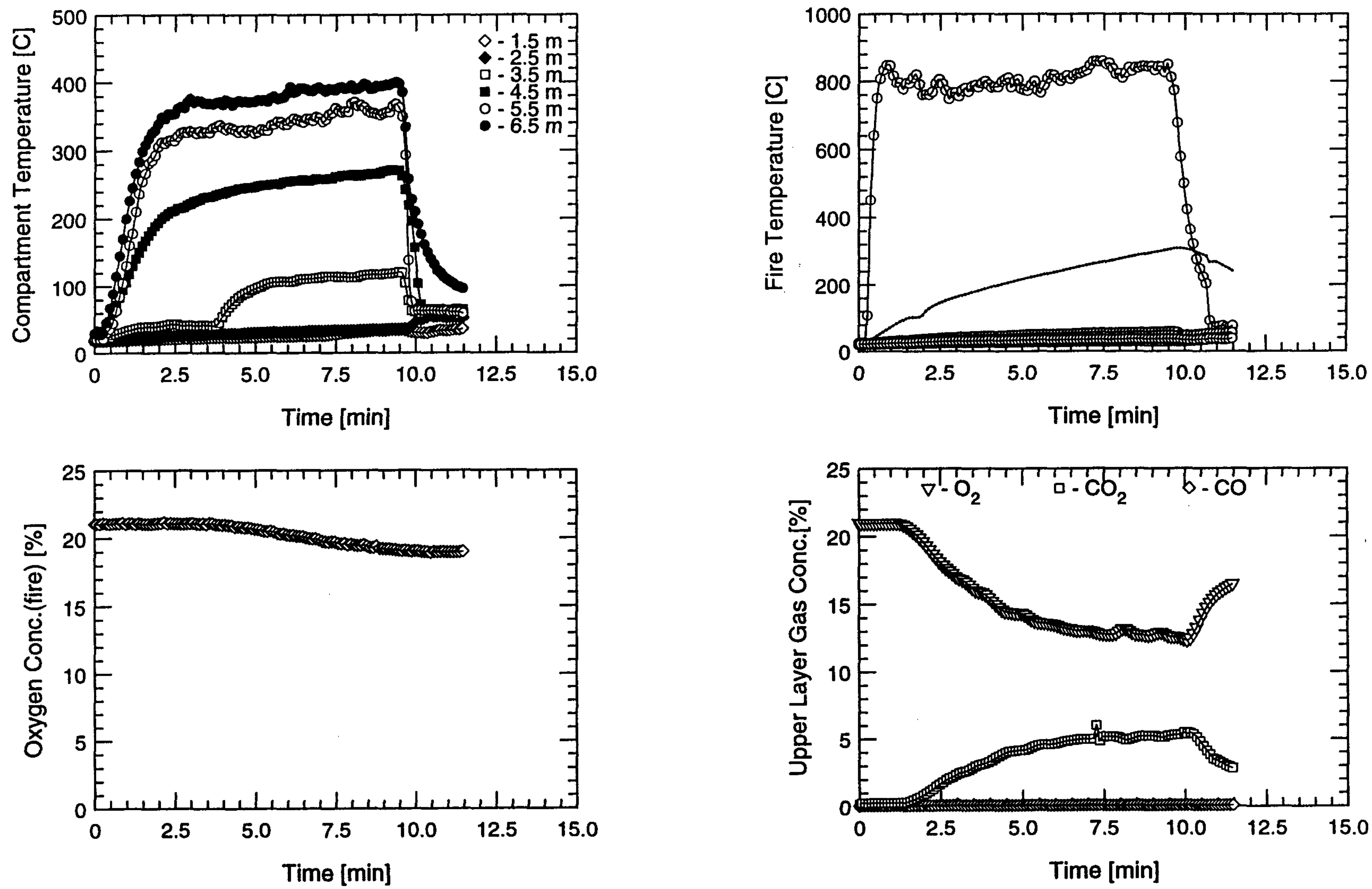

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #29

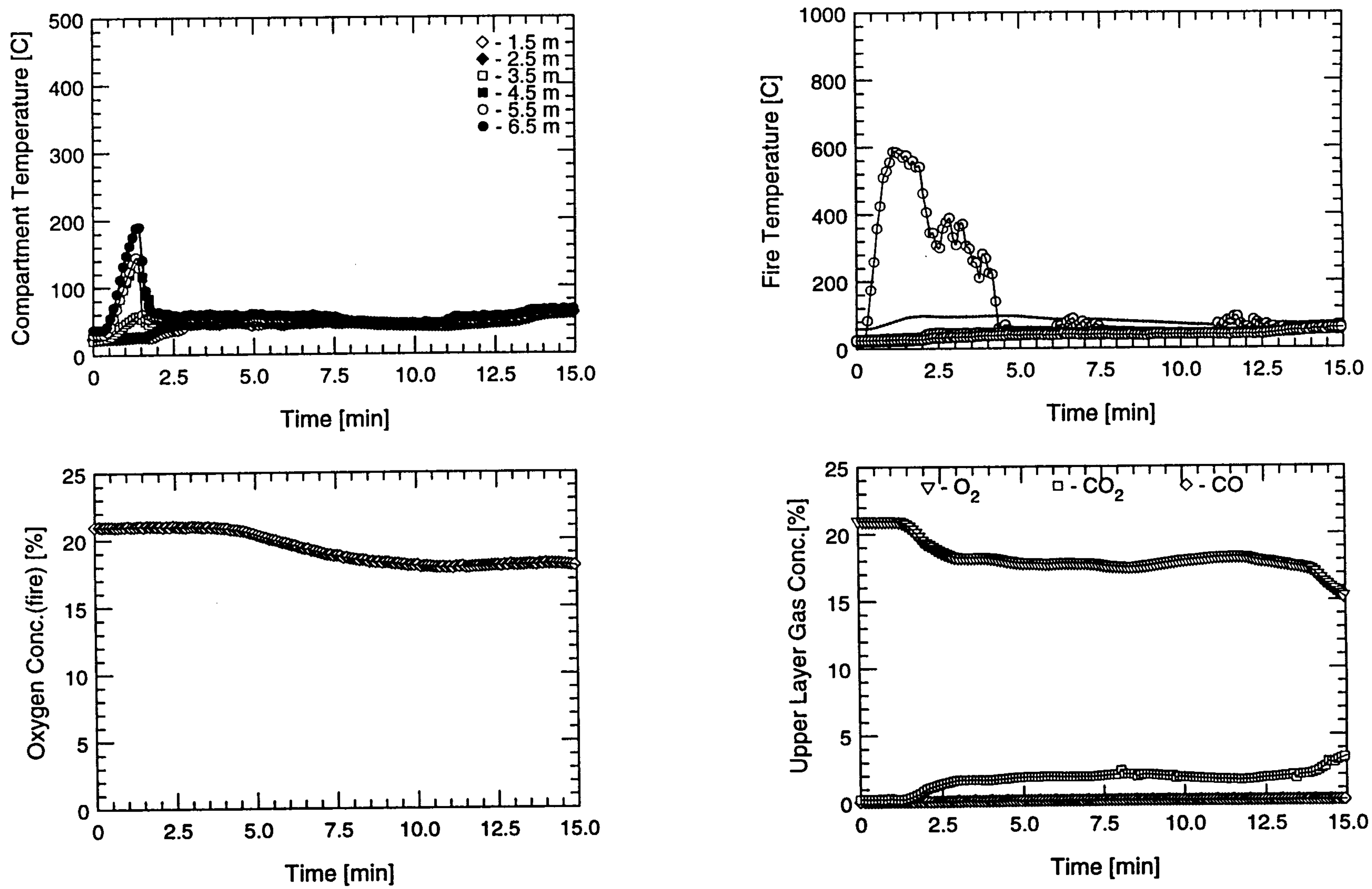


Compartment Temperature [C]
500
400
300
200
100
0
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #30

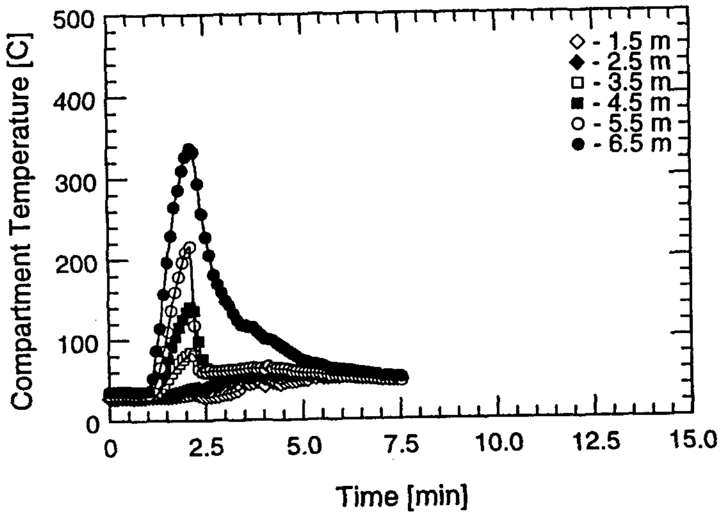

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #31

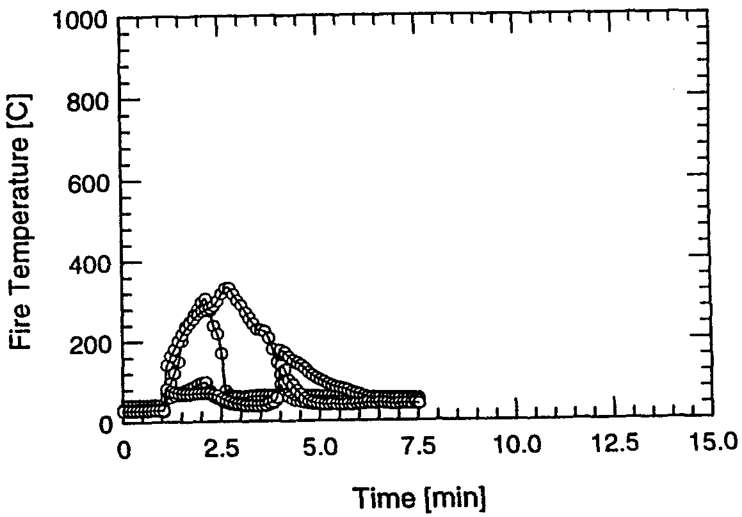


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

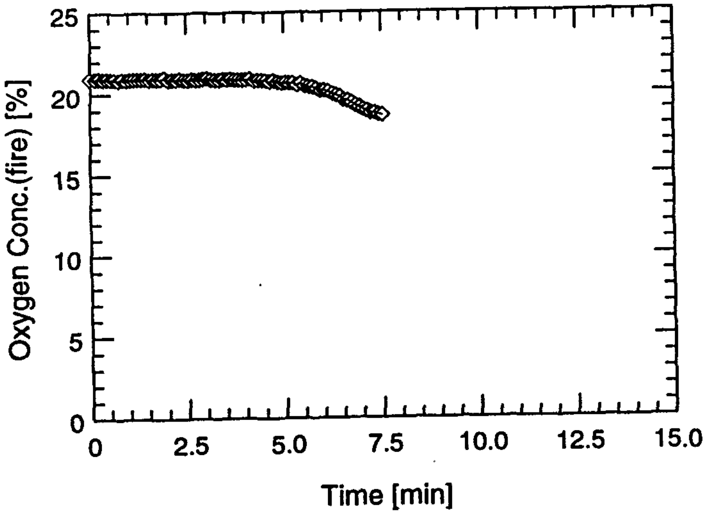
Test #32



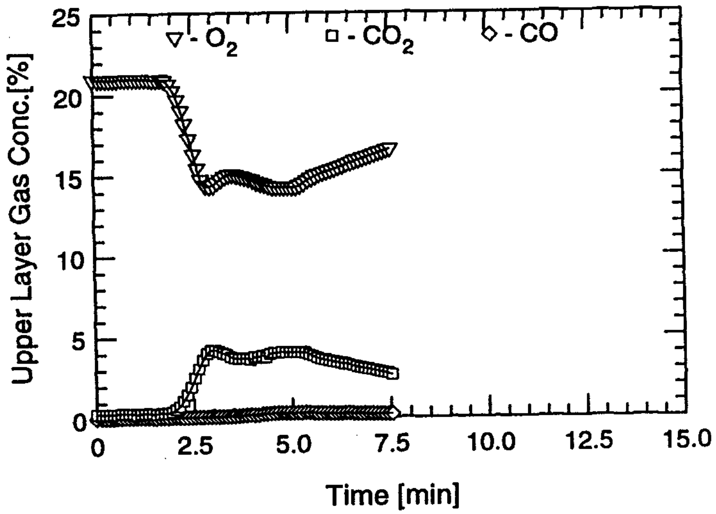
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m



Fire Temperature [C]
Time [min]

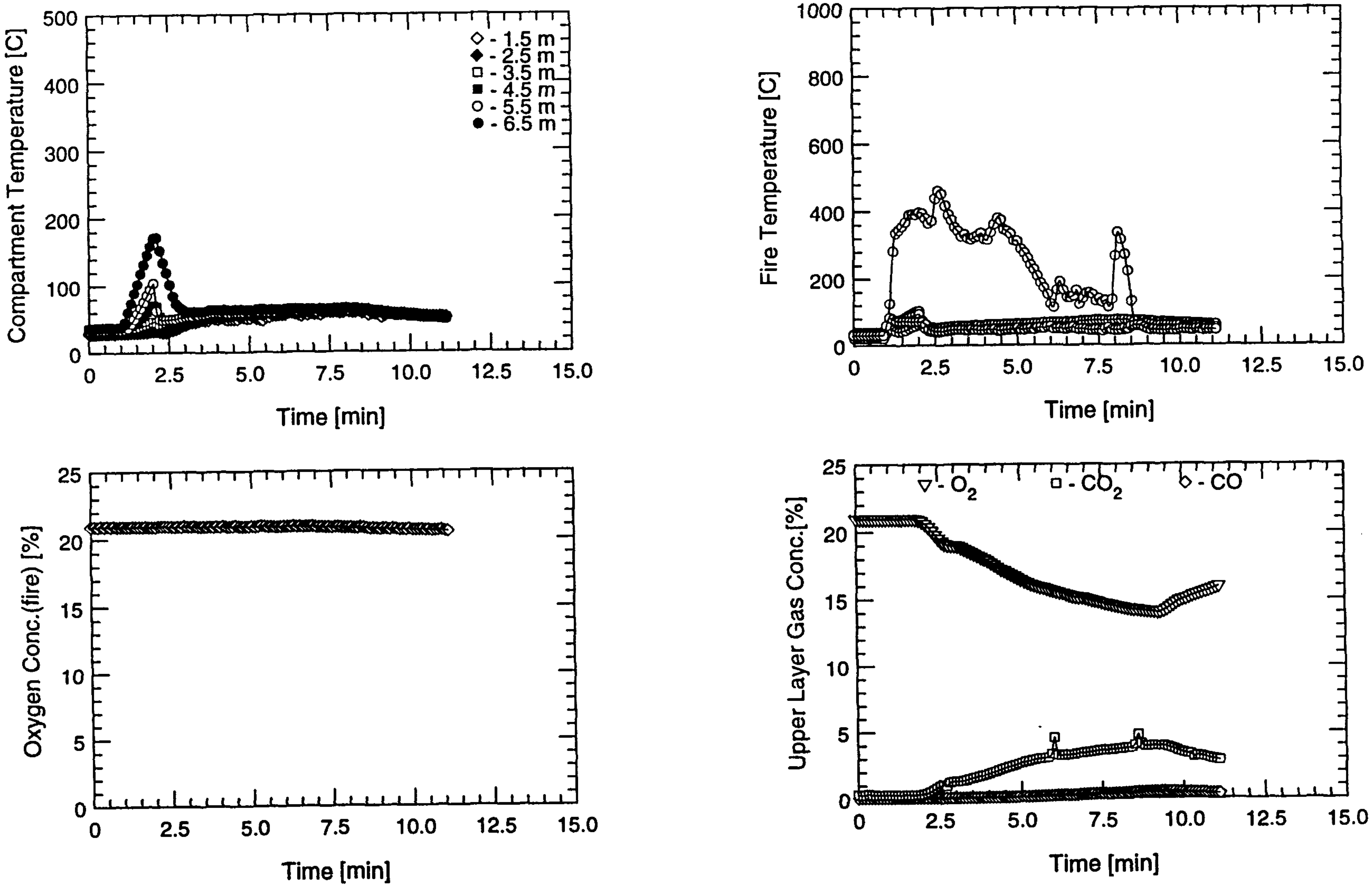


Oxygen Conc.(fire) [%]
Time [min]

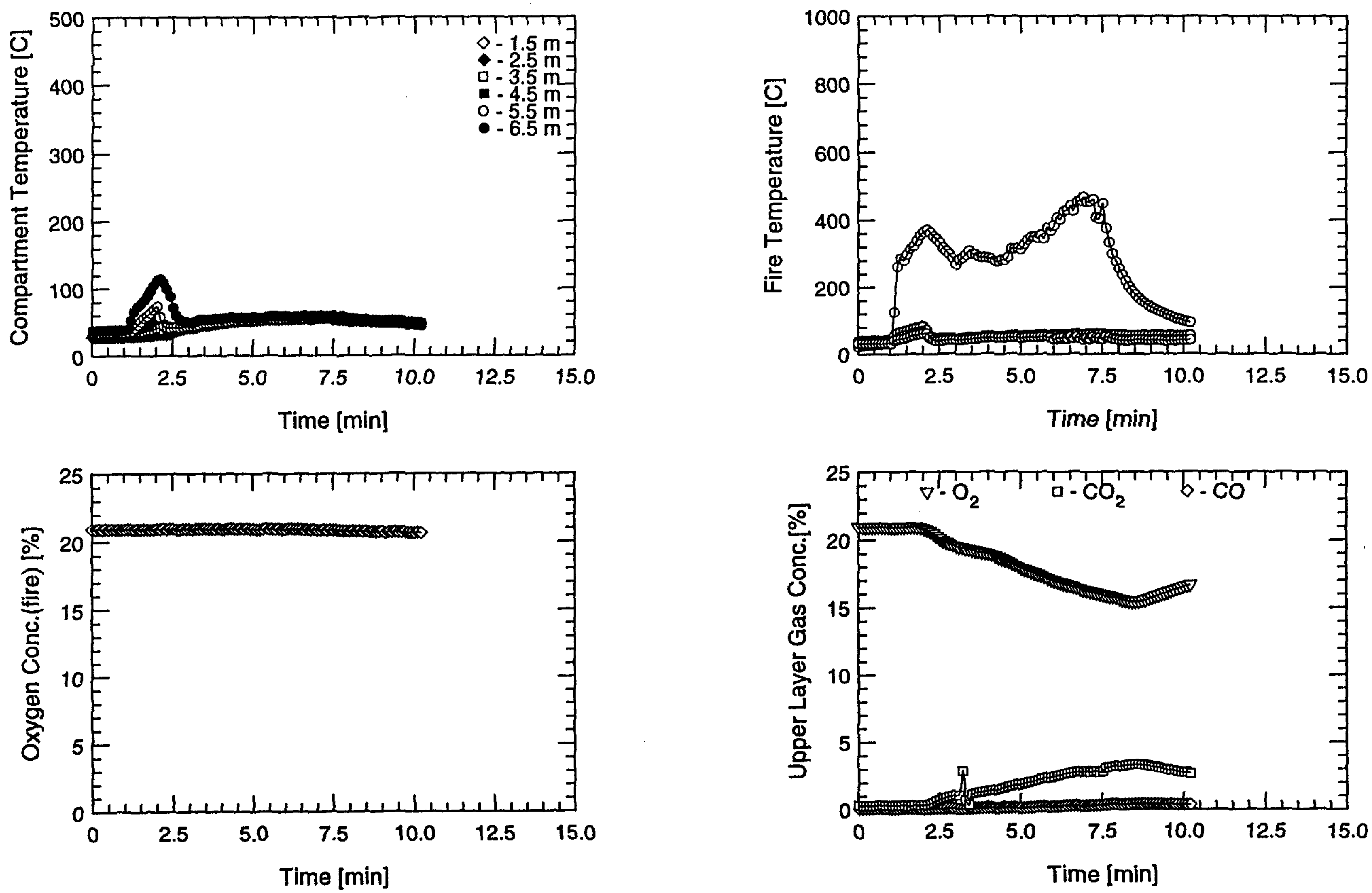


Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #33

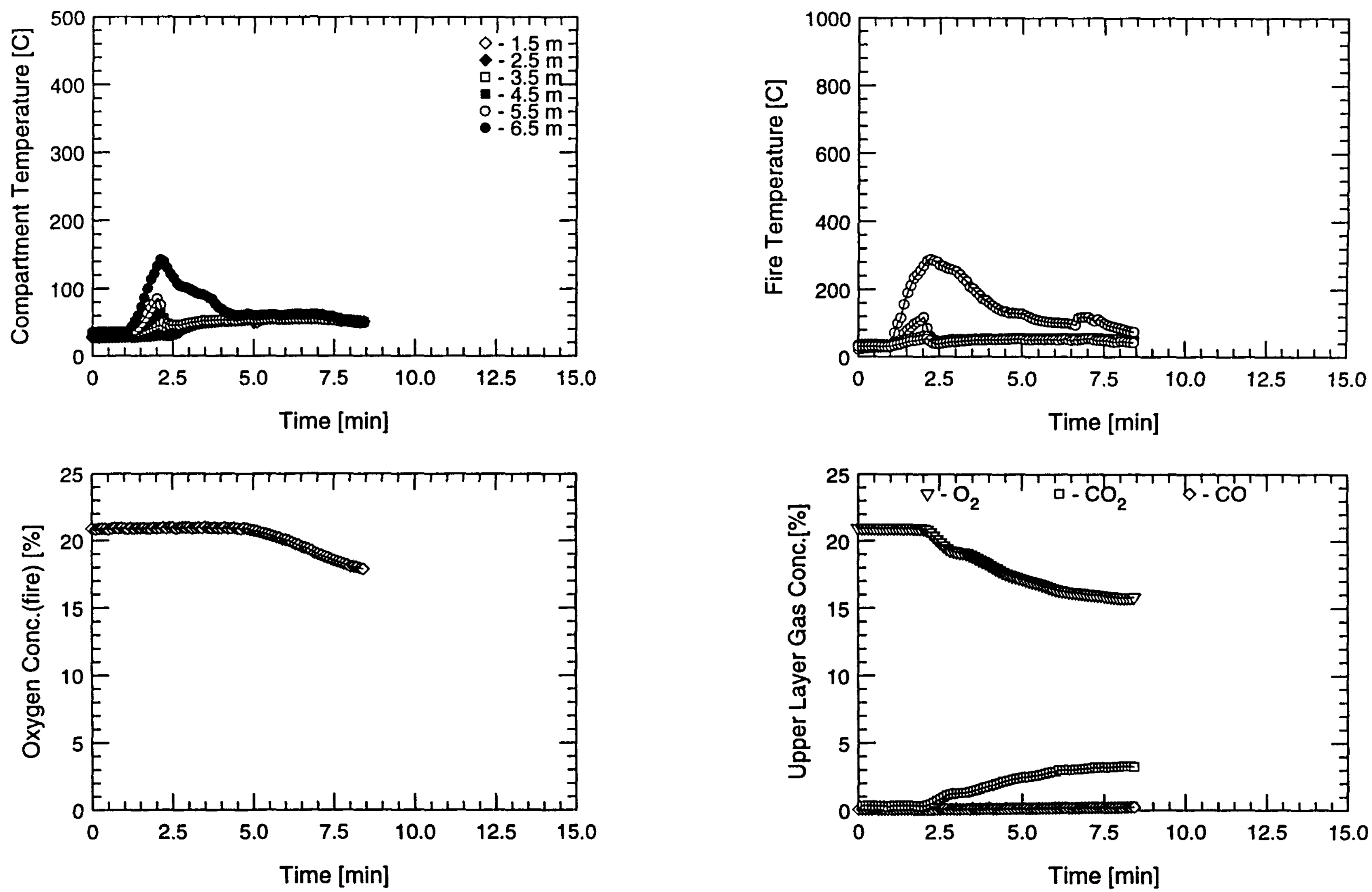

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #34

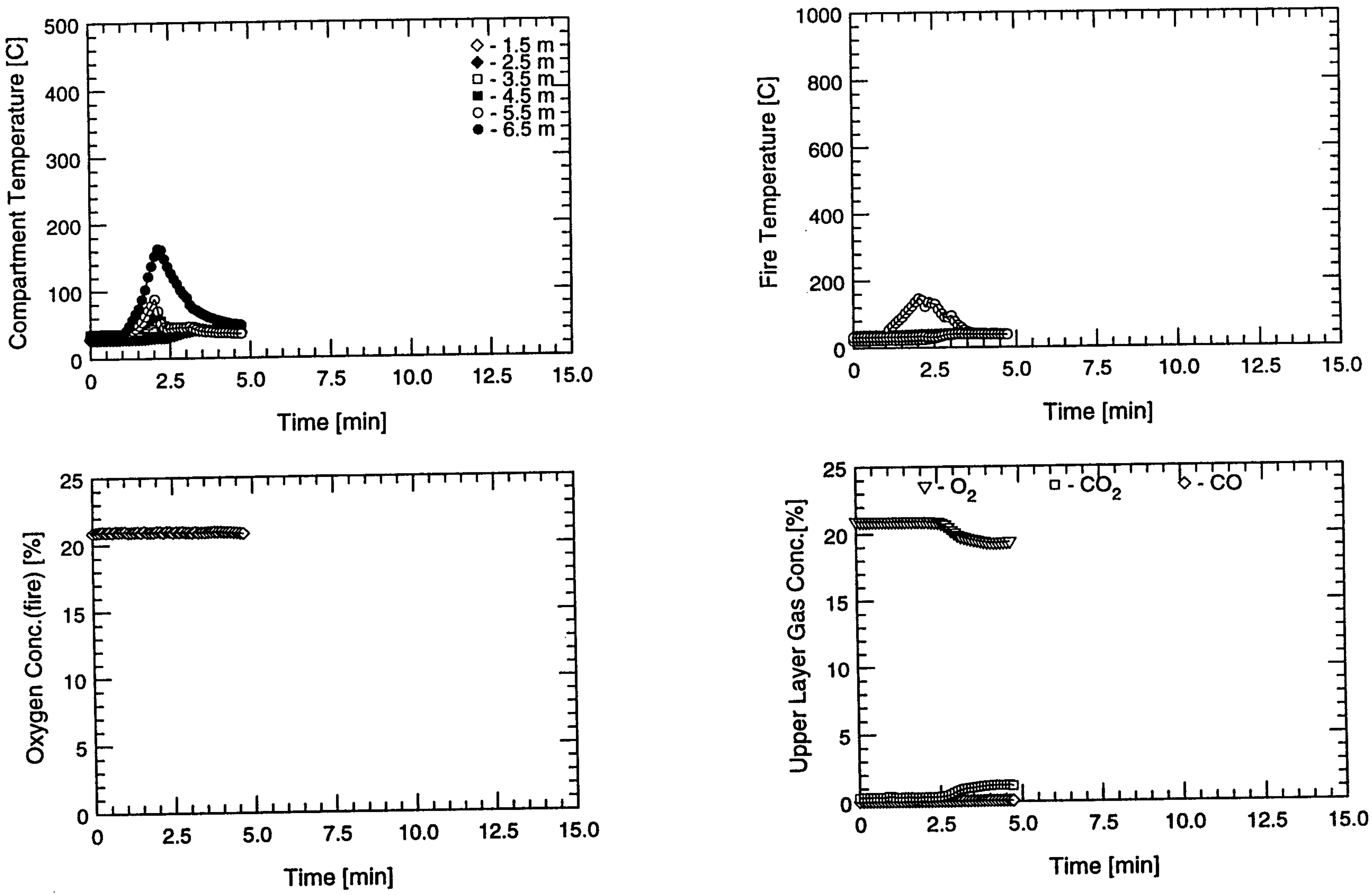


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

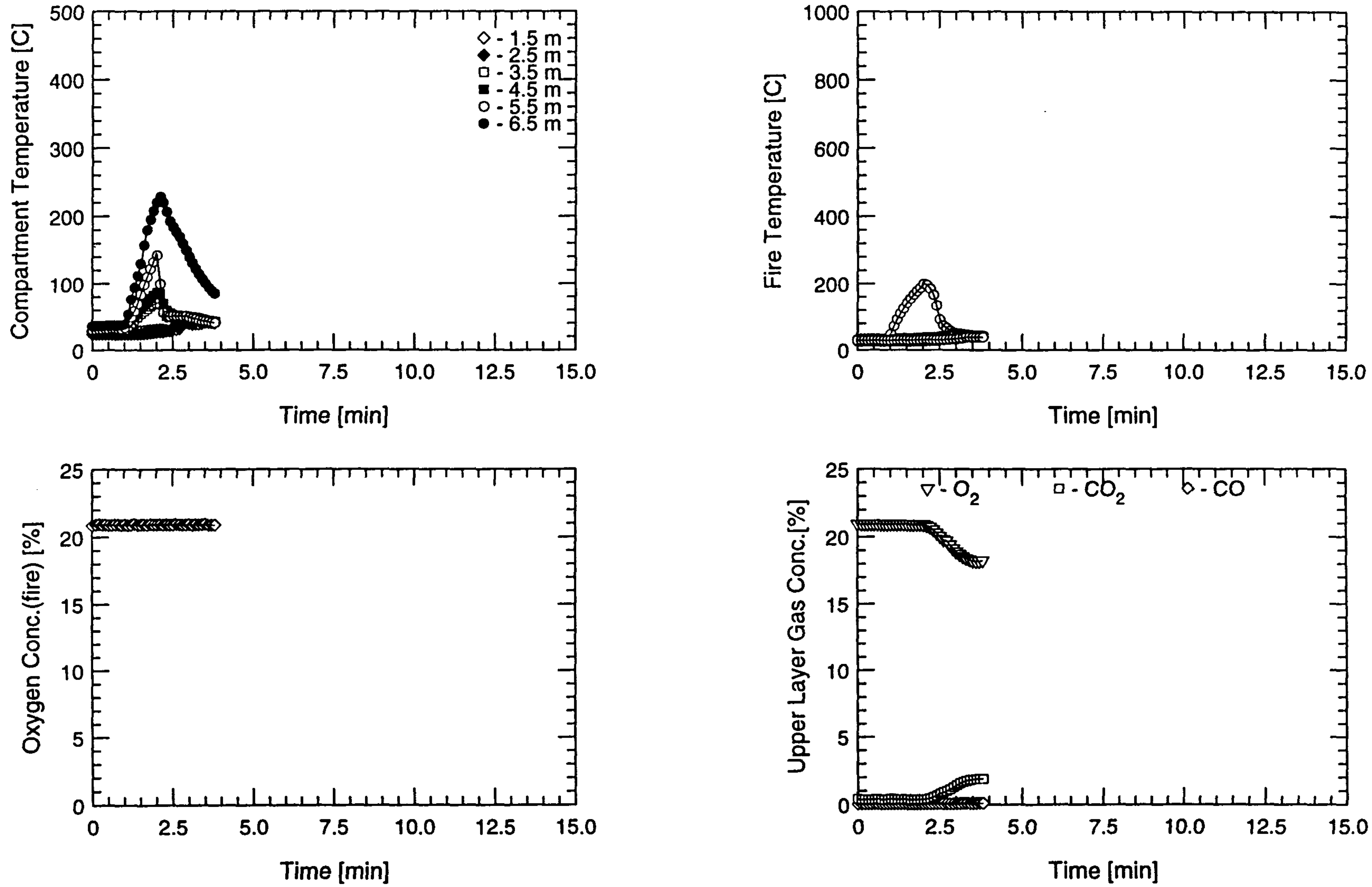
Test #35


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

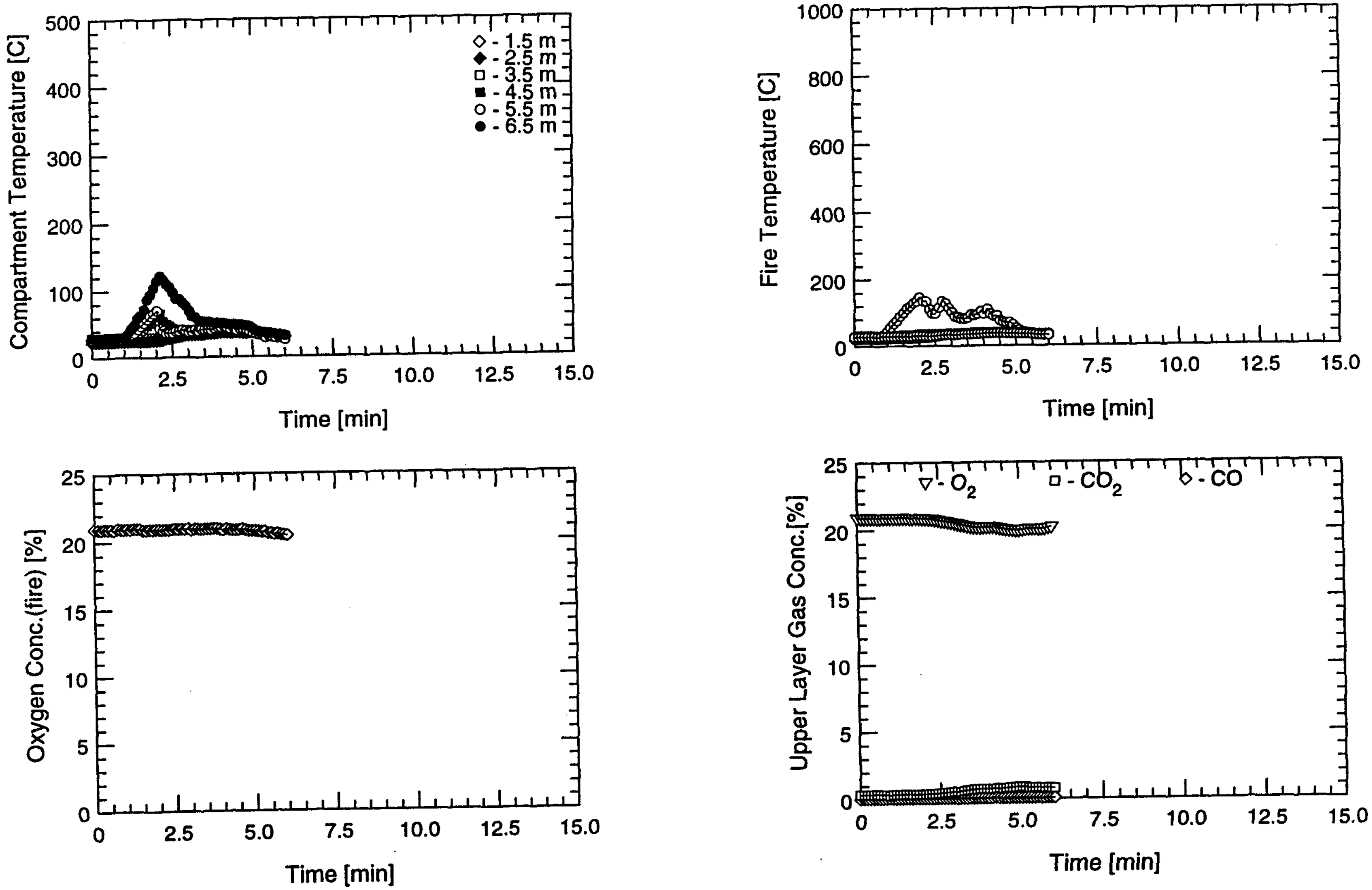
Test #36


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

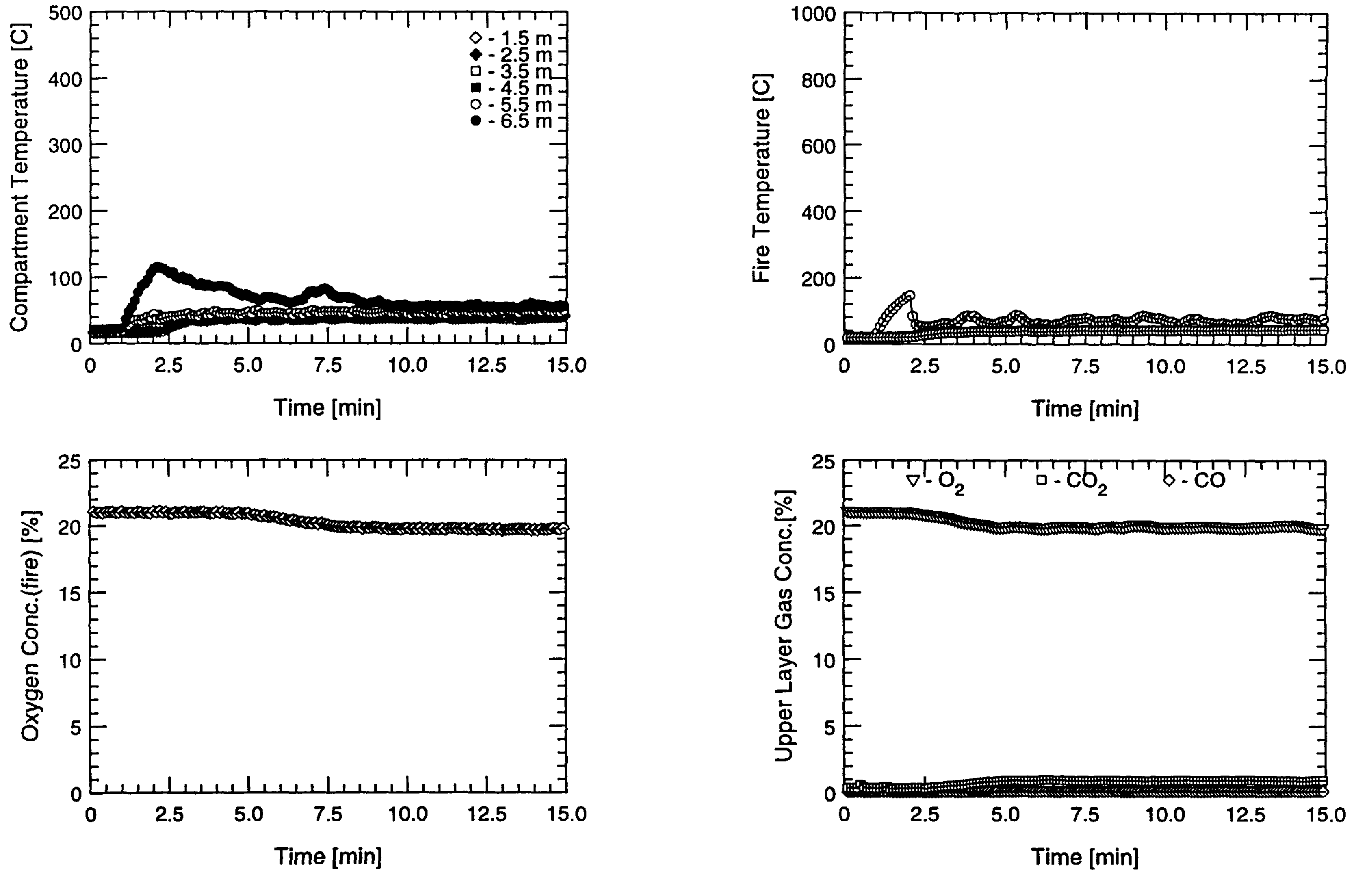
Test #37


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #38

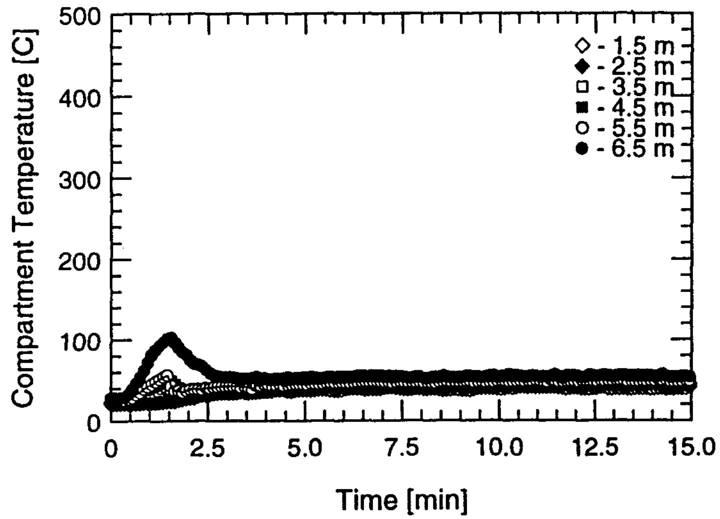

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

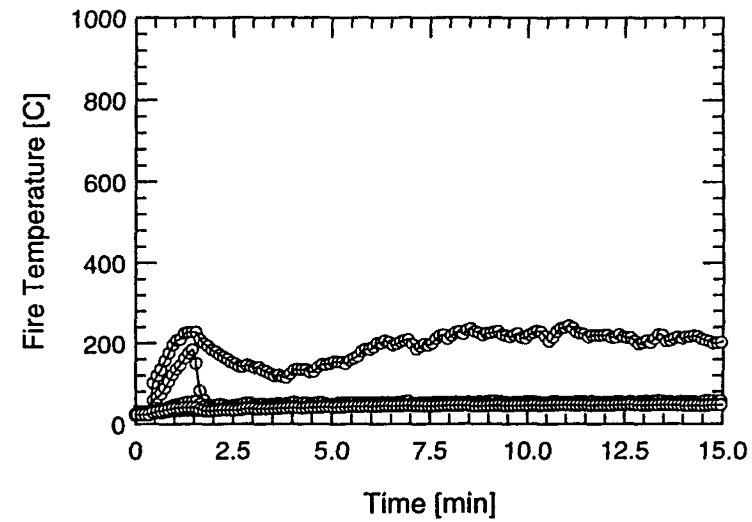
Test #39

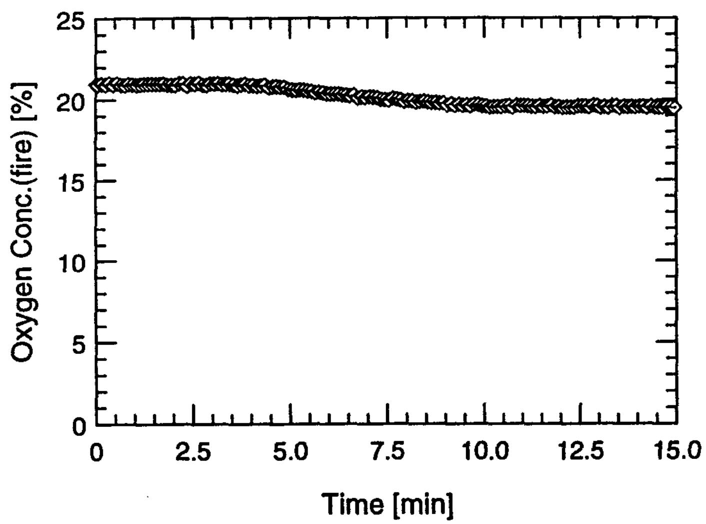


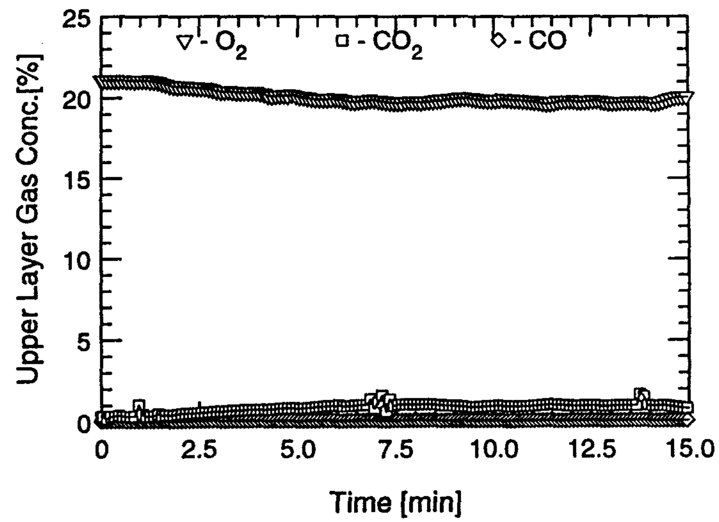
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #40

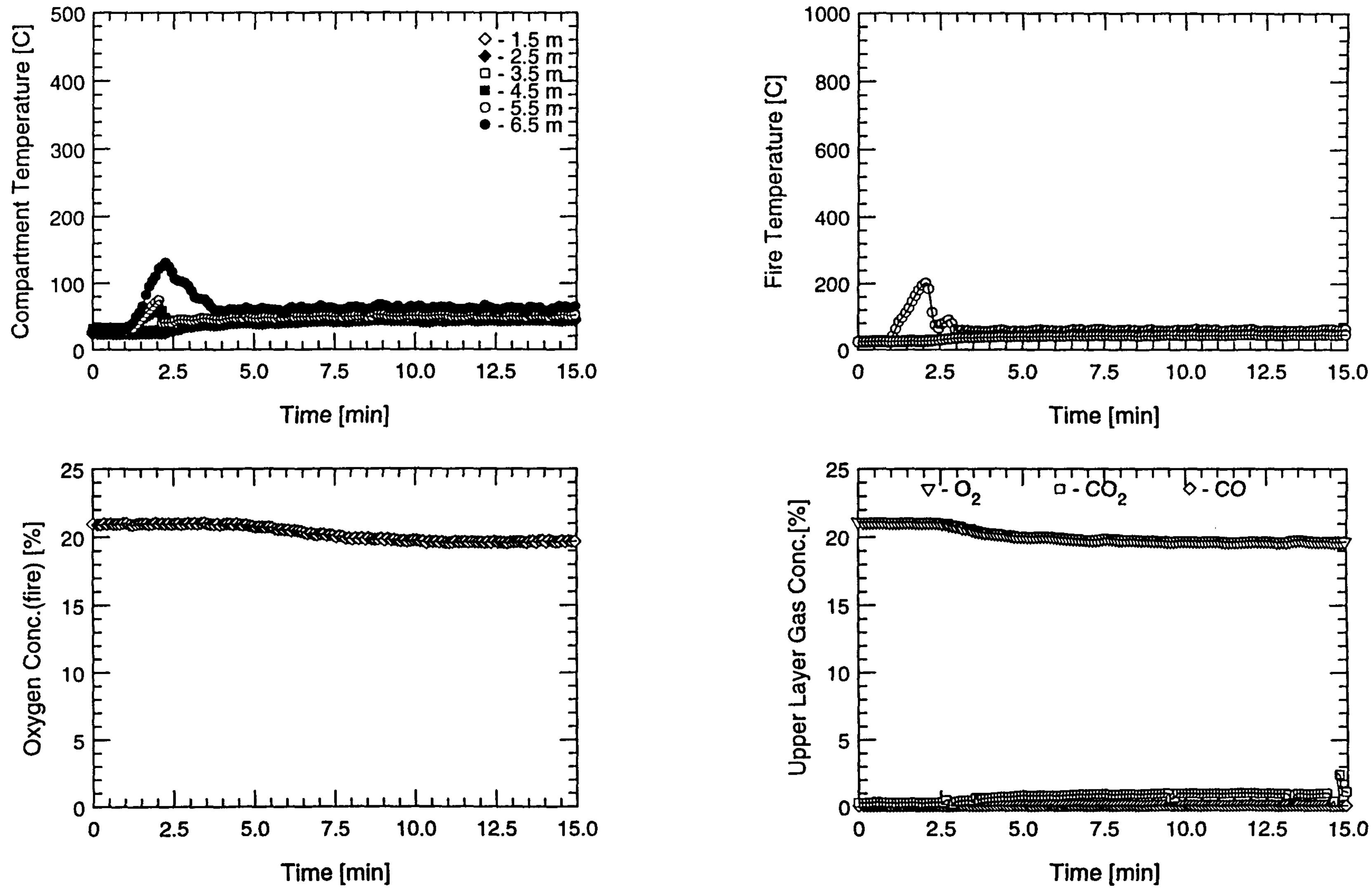

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m


Fire Temperature [C]
Time [min]

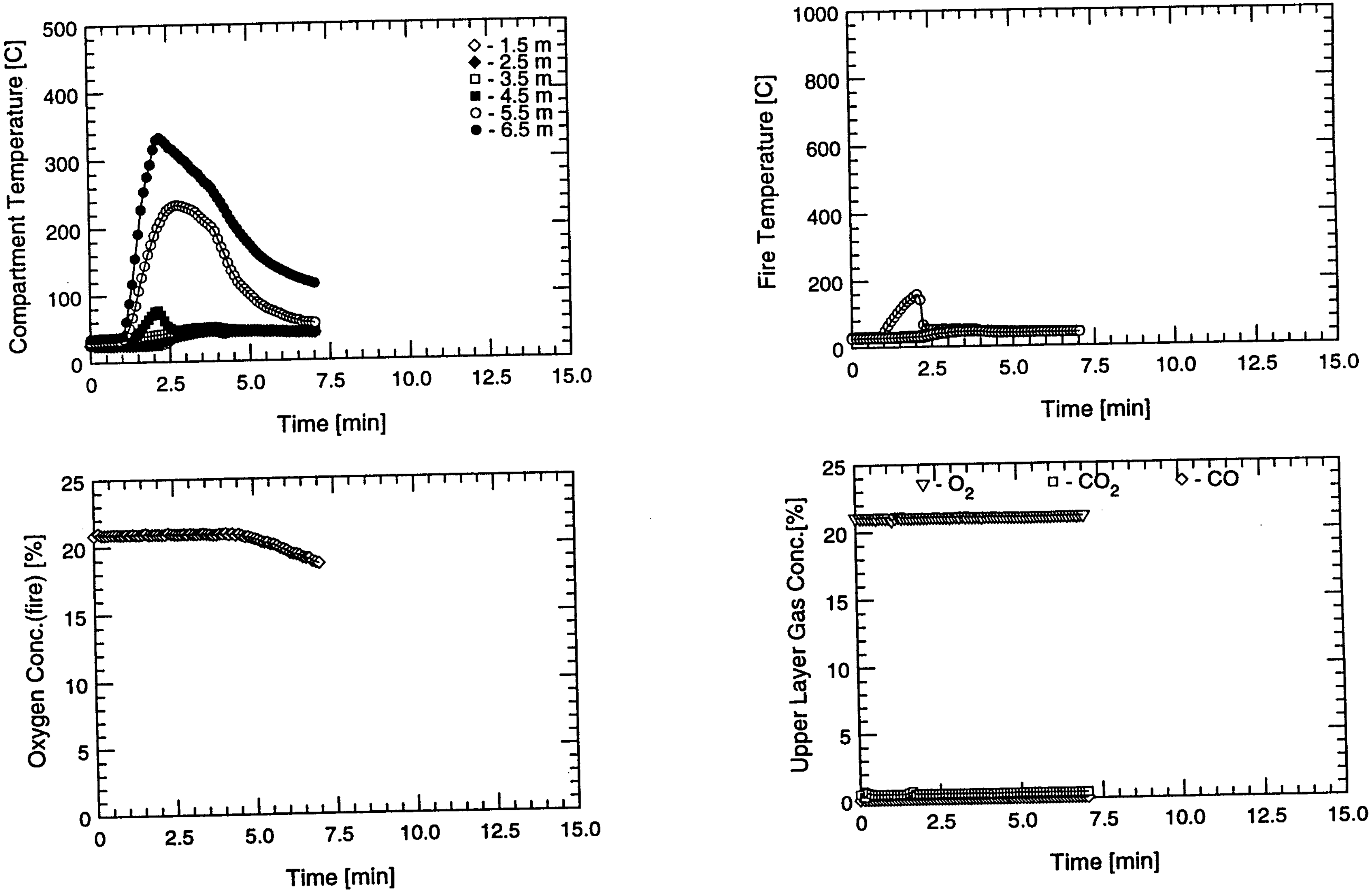

Oxygen Conc.(fire) [%]
Time [min]


Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #41

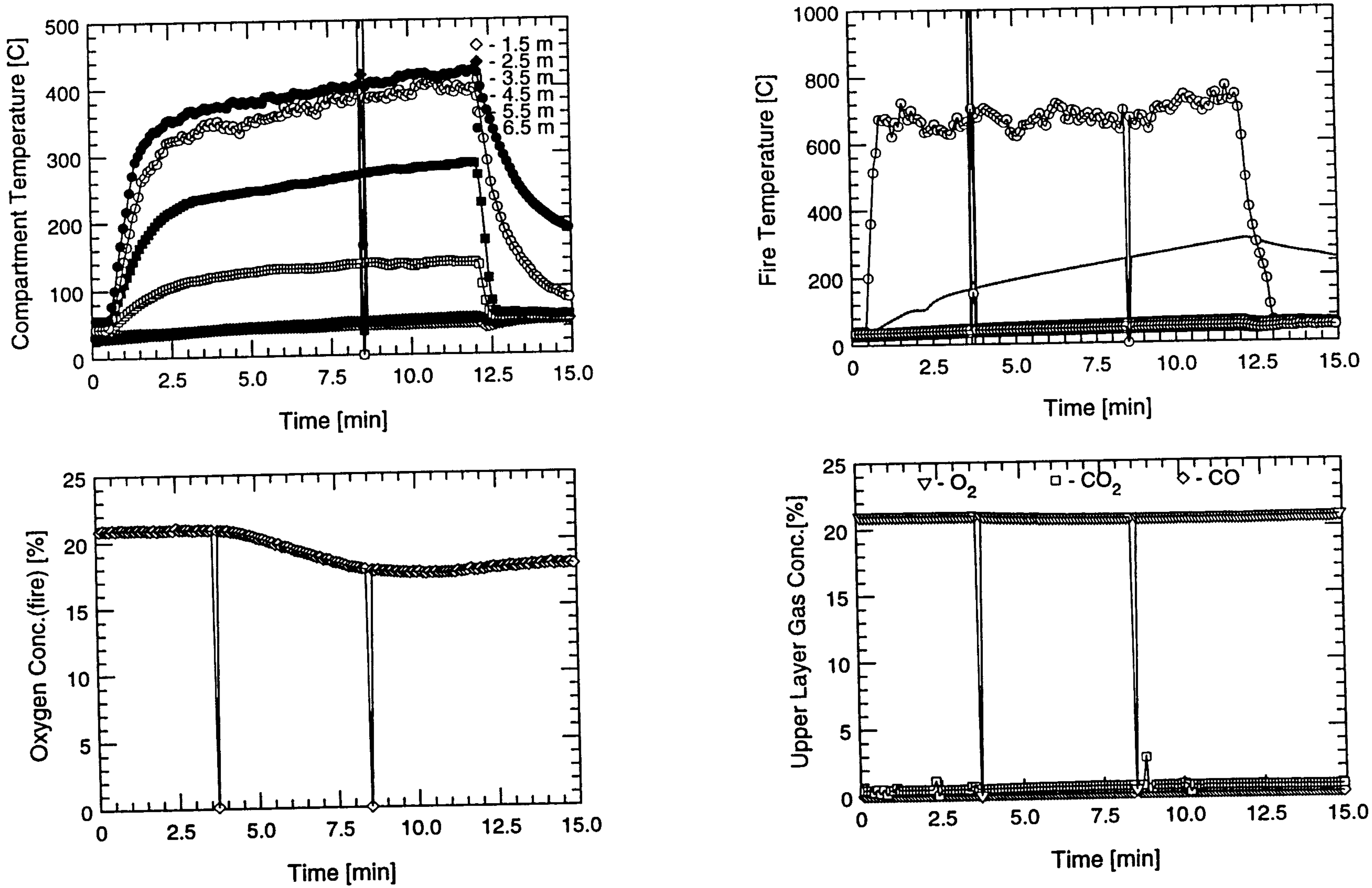

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #42



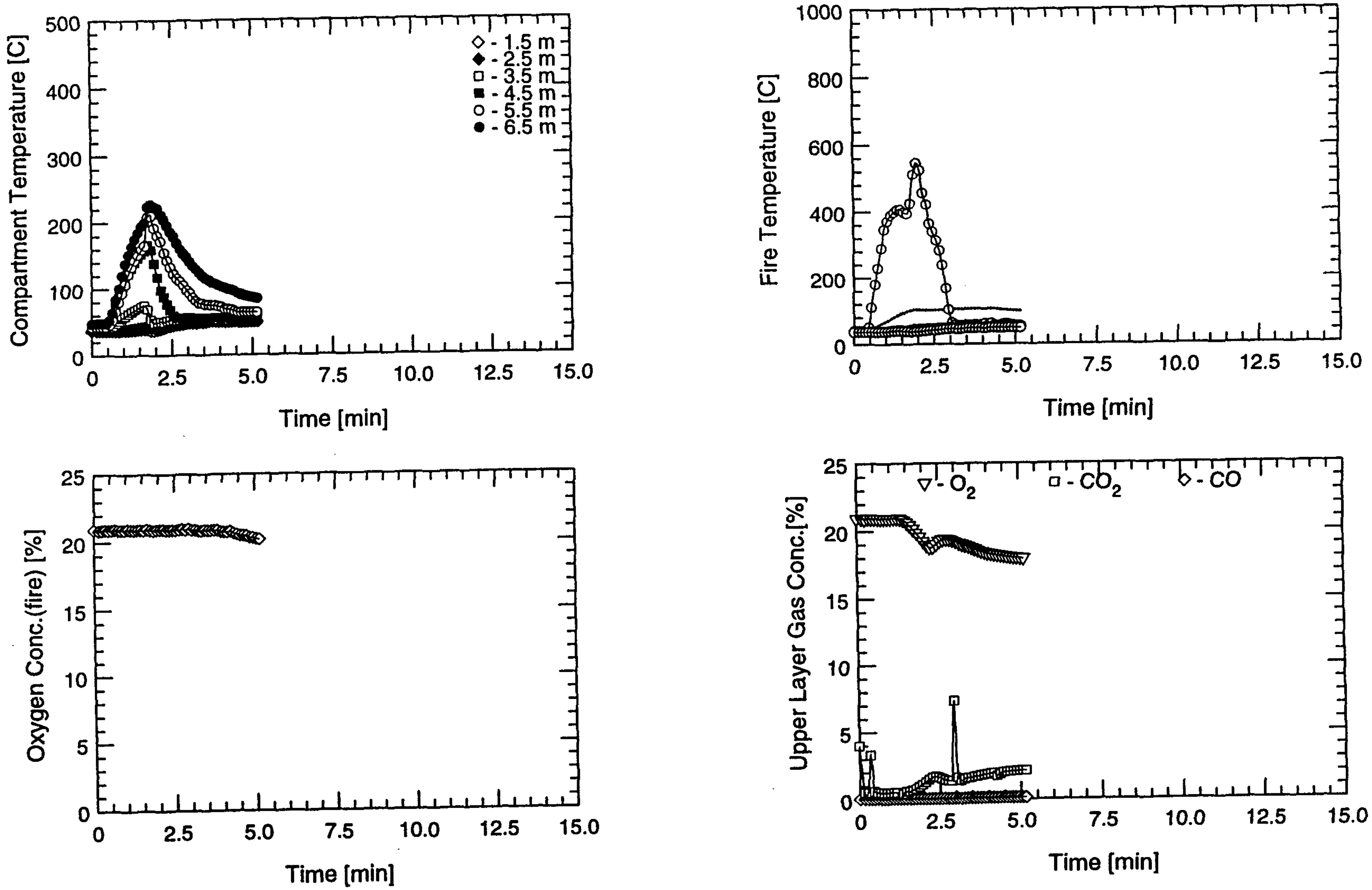
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
0
2.5
5.0
7.5
10.0
12.5
15.0
Fire Temperature [C]
1000
800
600
400
200
0
Oxygen Conc.(fire) [%]
25
20
15
10
5
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO

Test #43

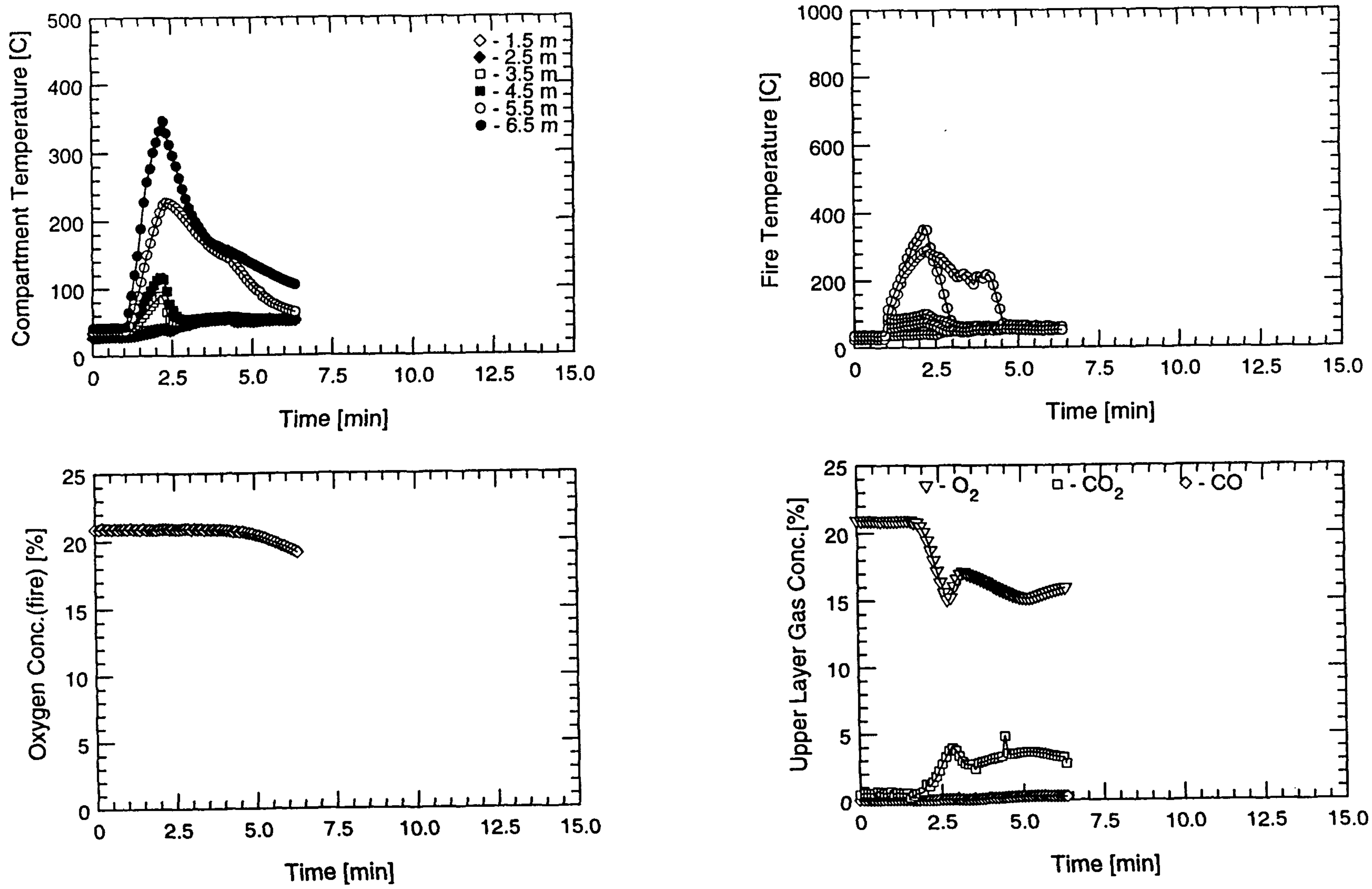


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
- 3.5 m
- 4.5 m
- 5.5 m
- 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #44

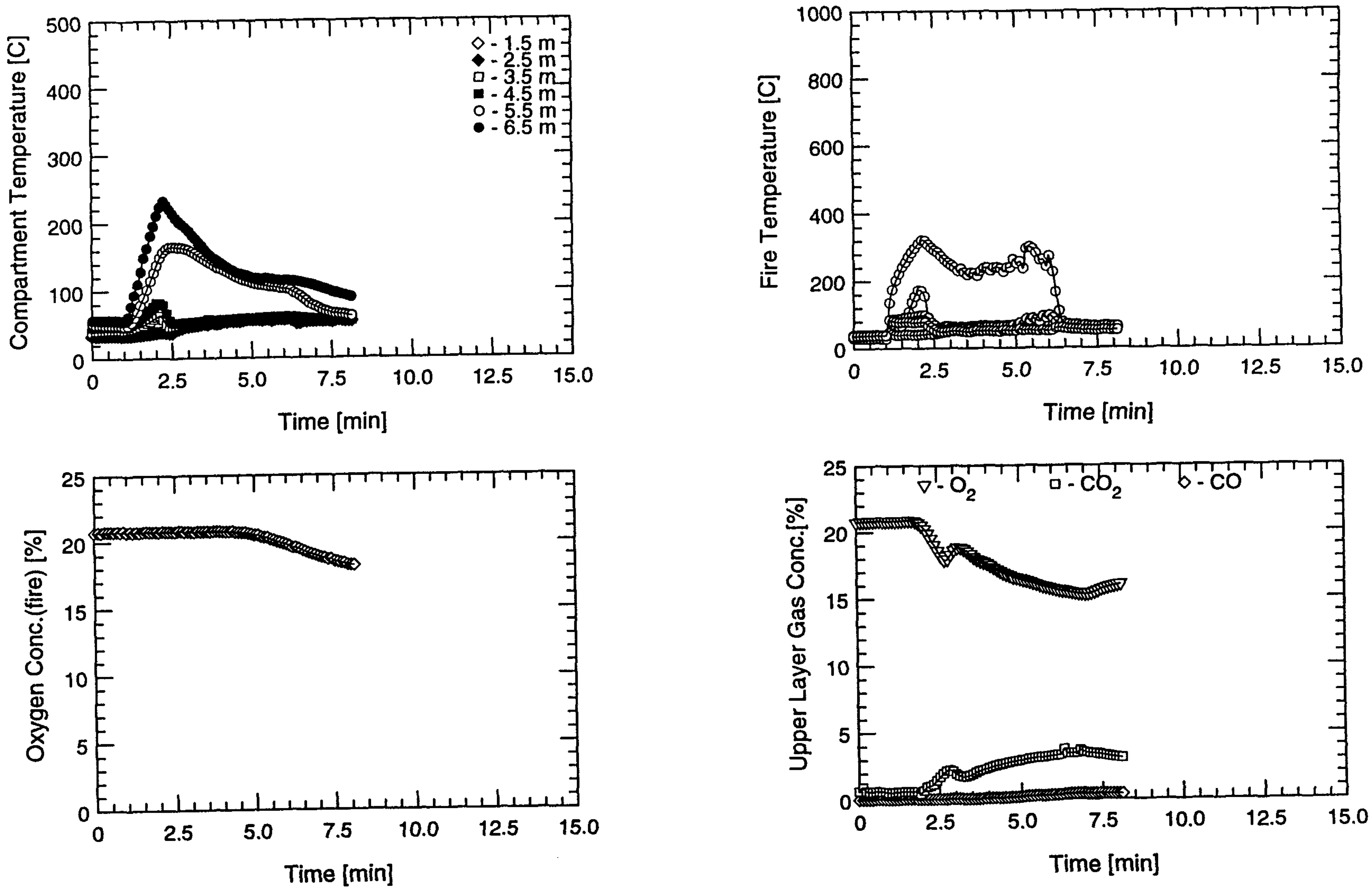

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O2
□ - CO2
◇ - CO

Test #45

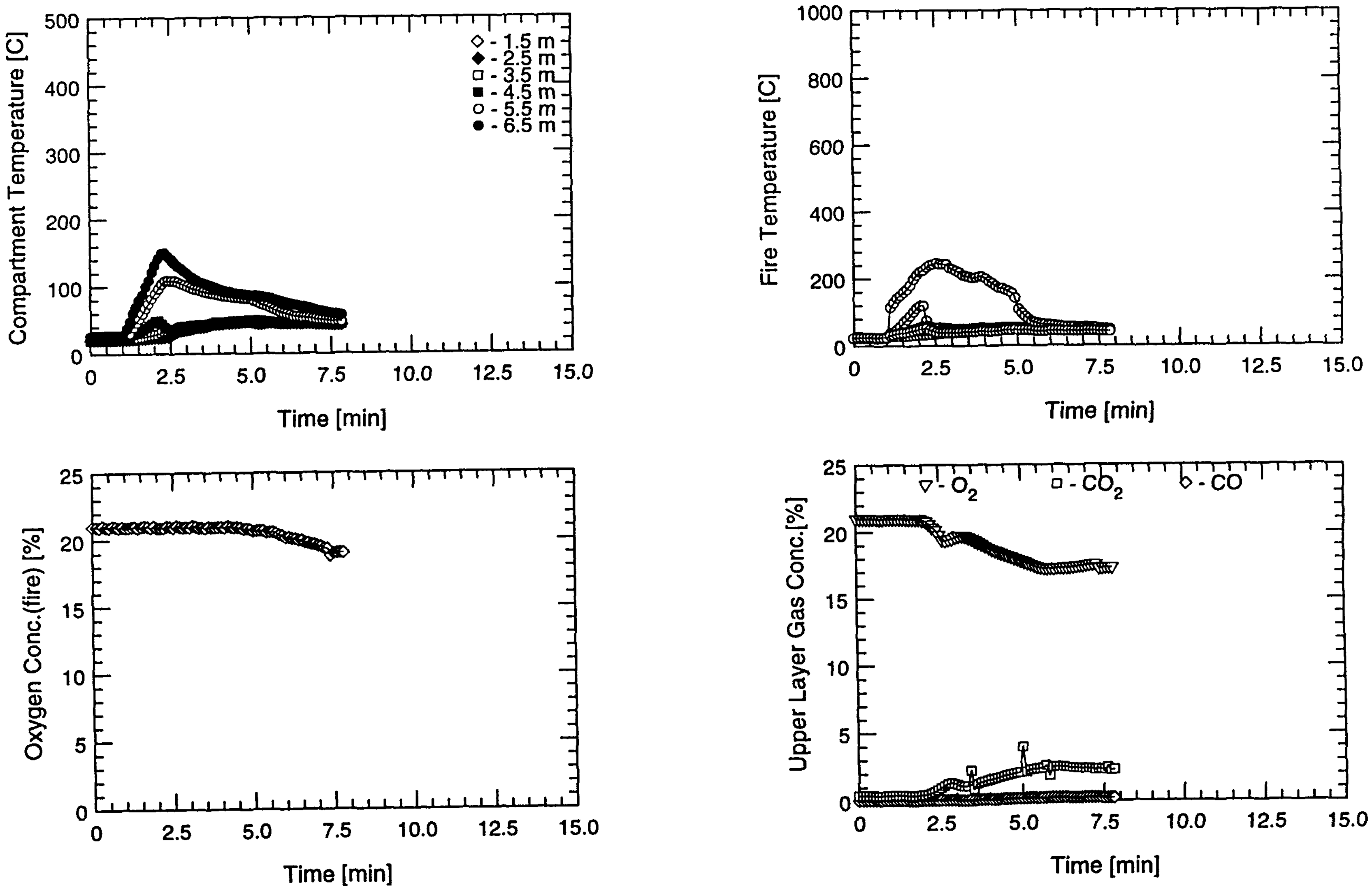


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #46

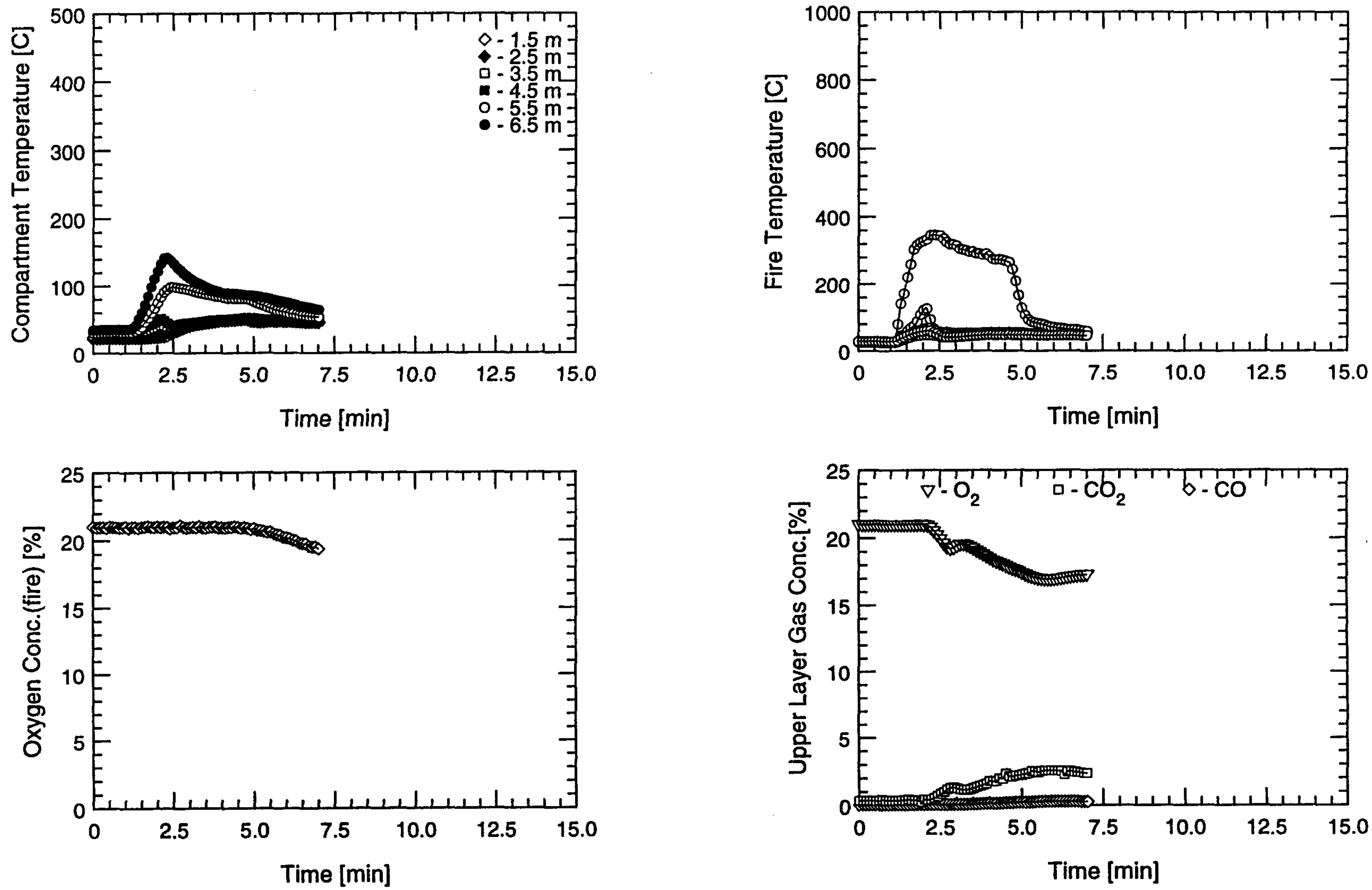

Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #47

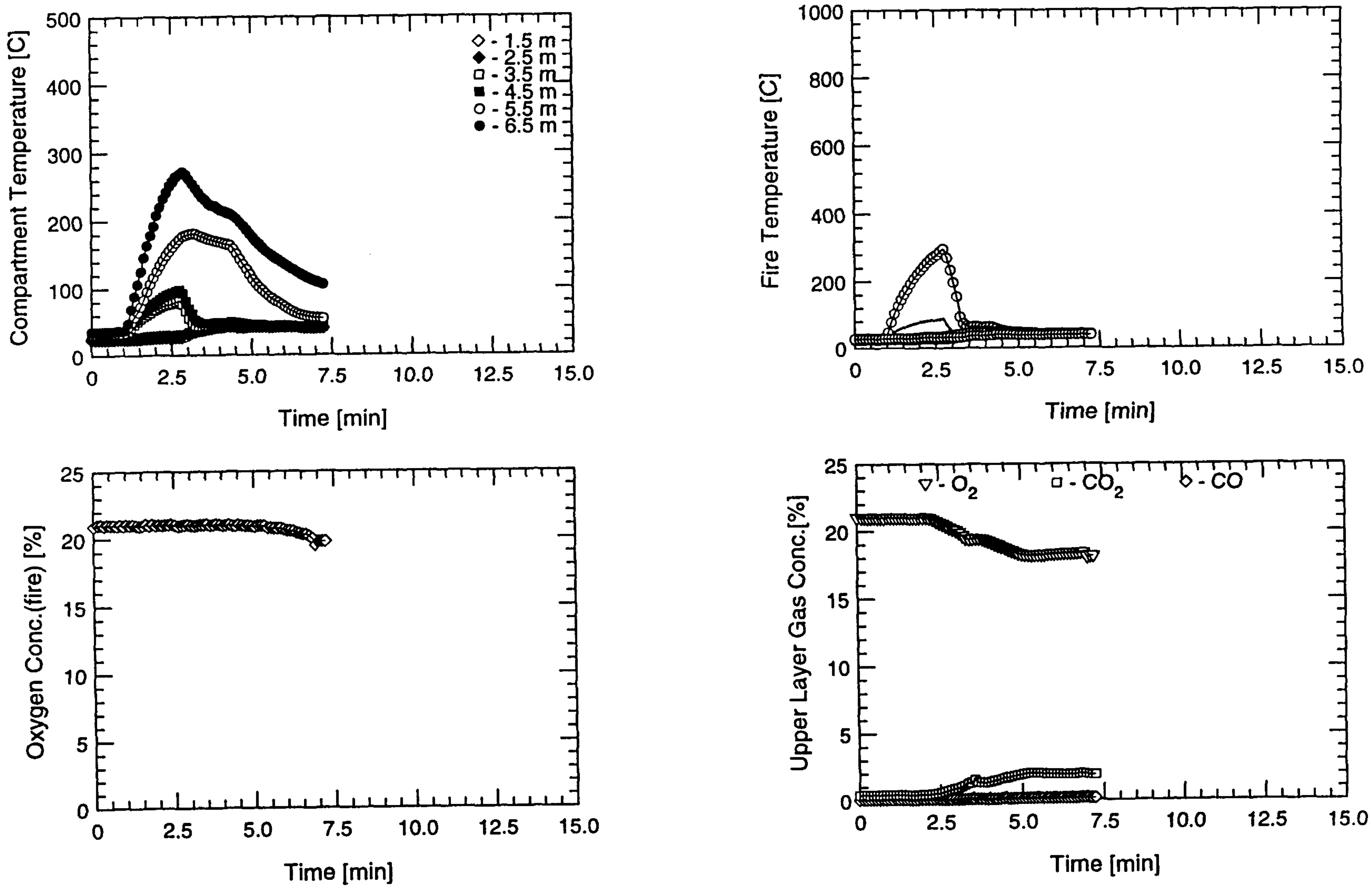


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

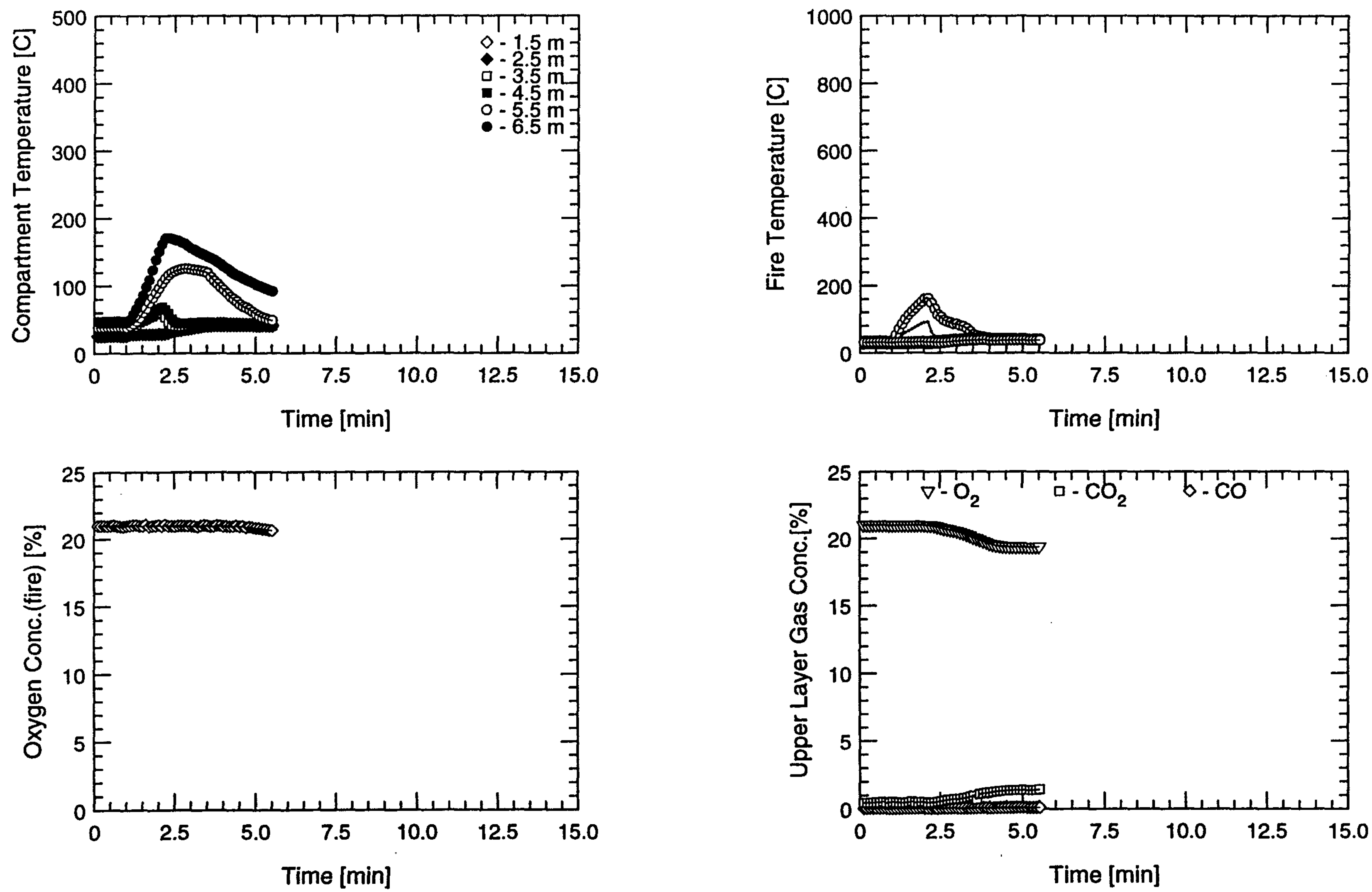
Test #48


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

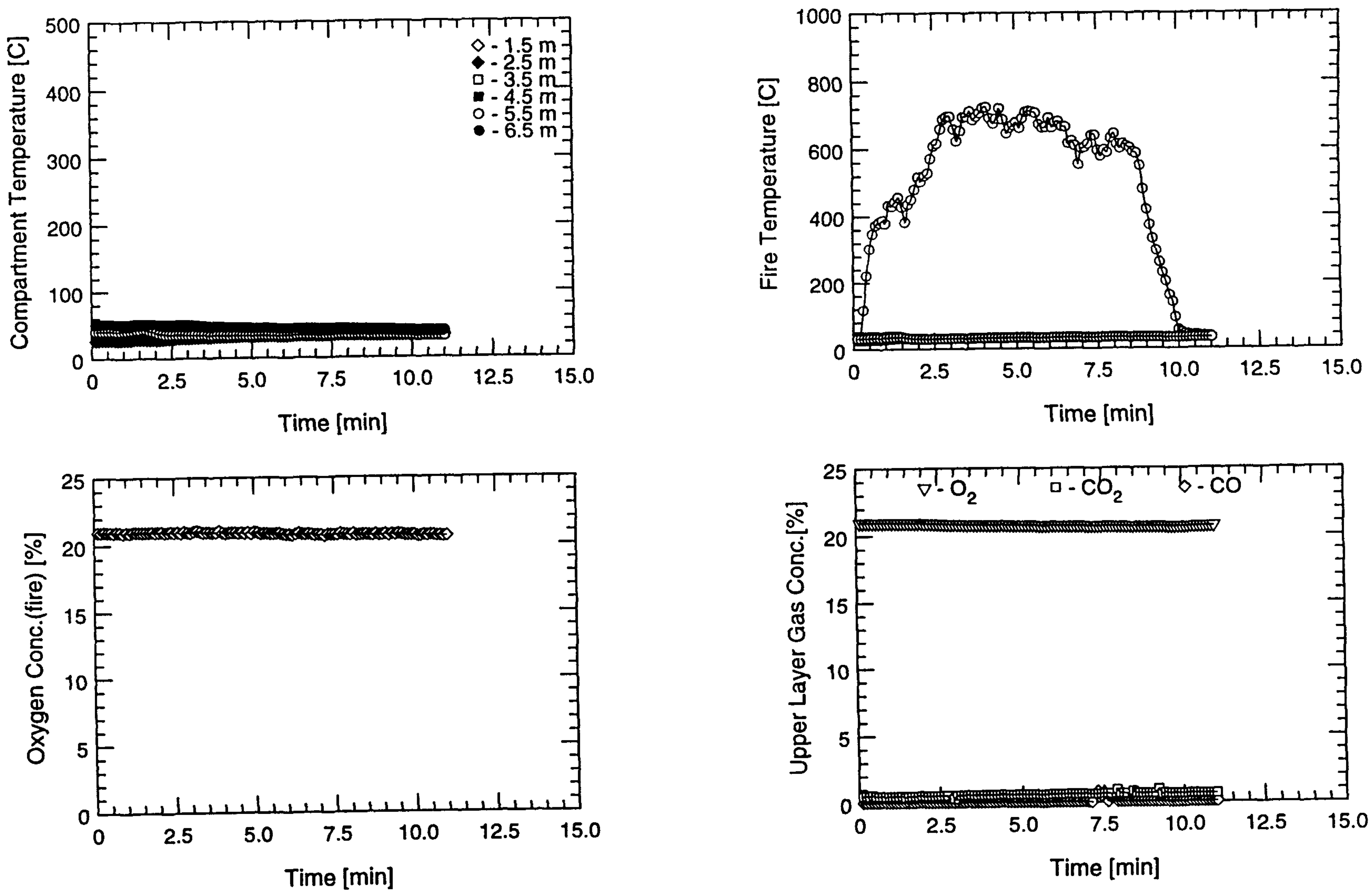
Test #49


◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Compartment Temperature [C]
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO
Upper Layer Gas Conc.[%]
Time [min]

Test #50

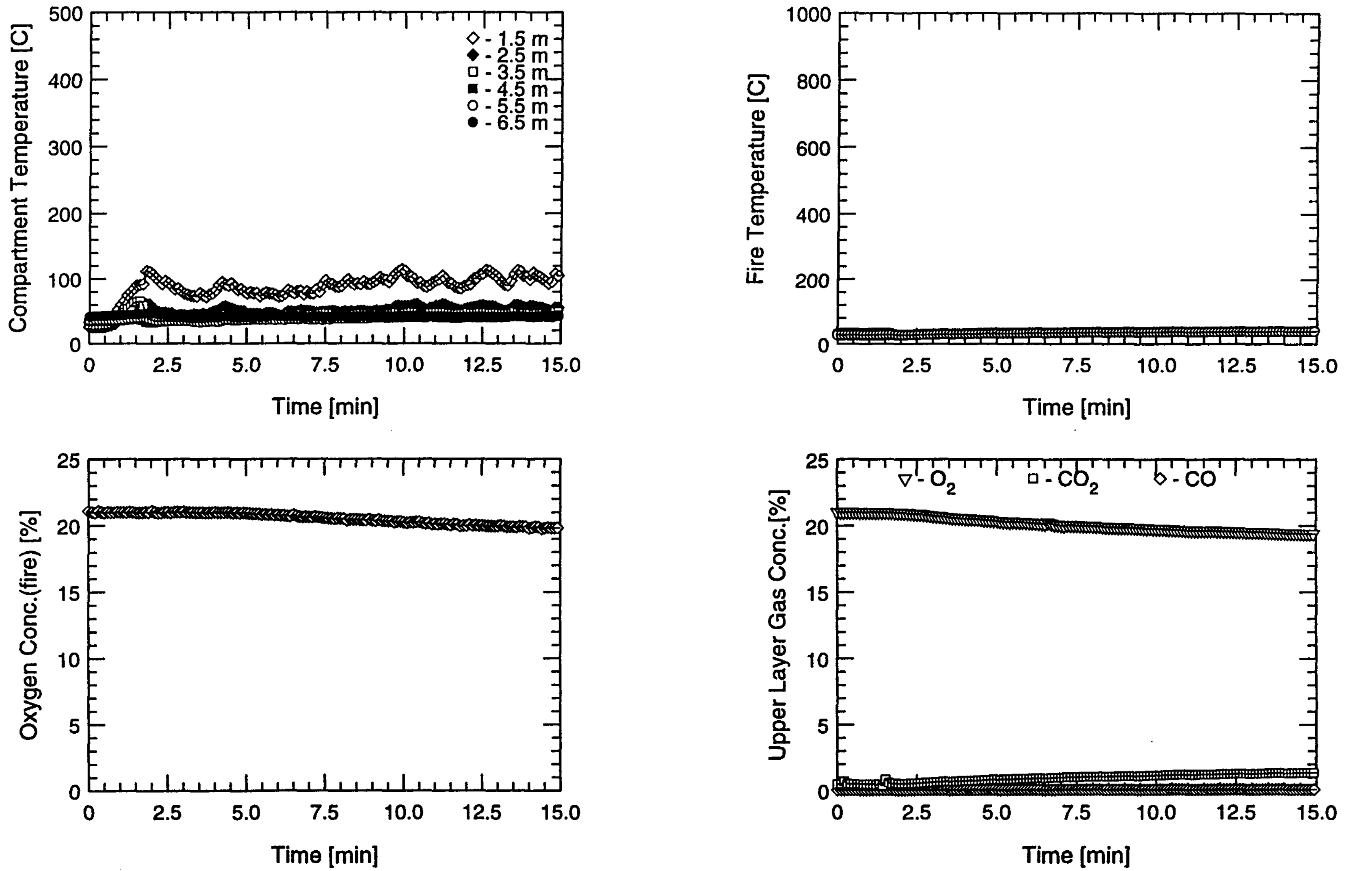

Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
0
2.5
5.0
7.5
10.0
12.5
15.0
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #51



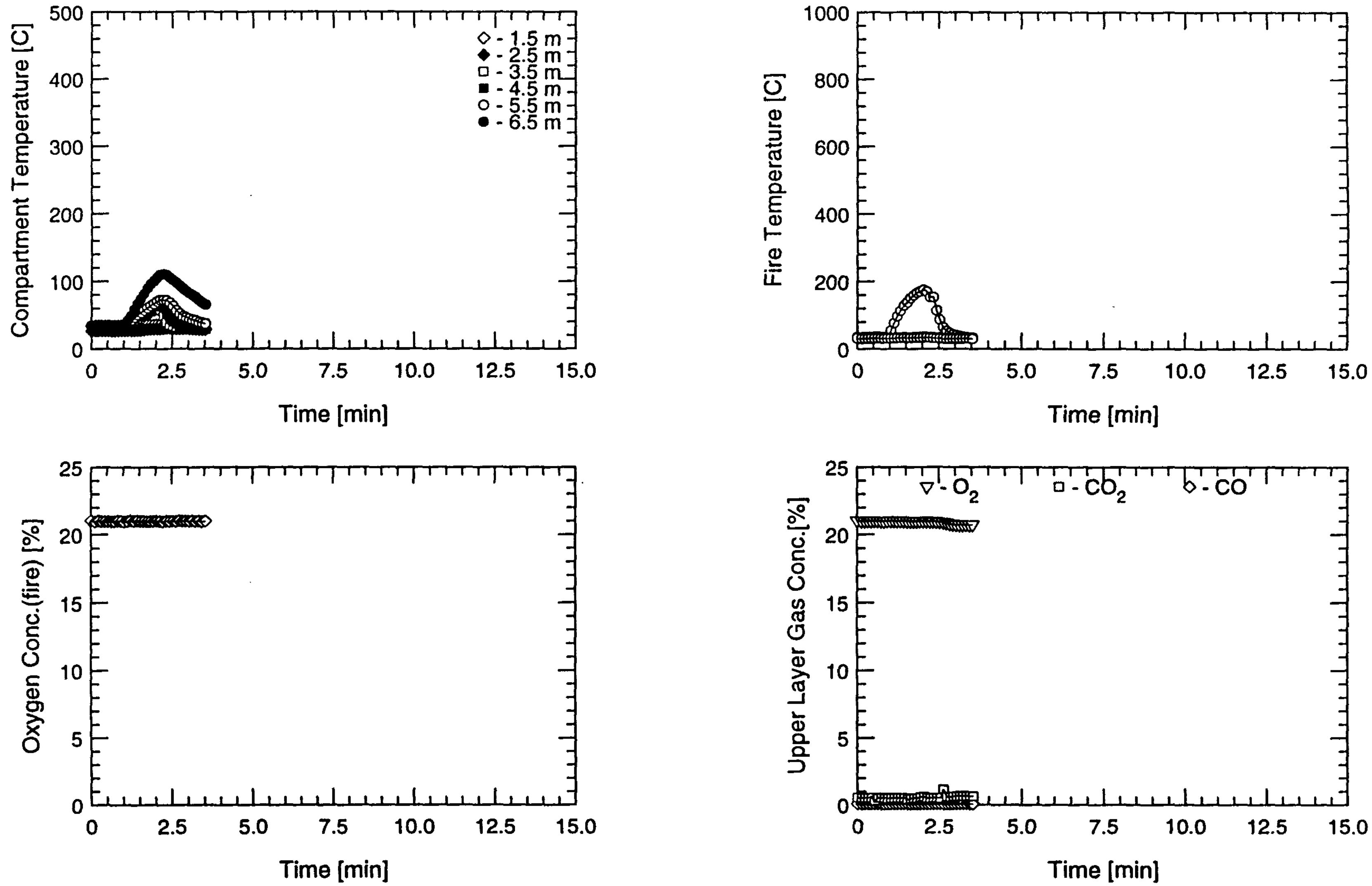
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #52

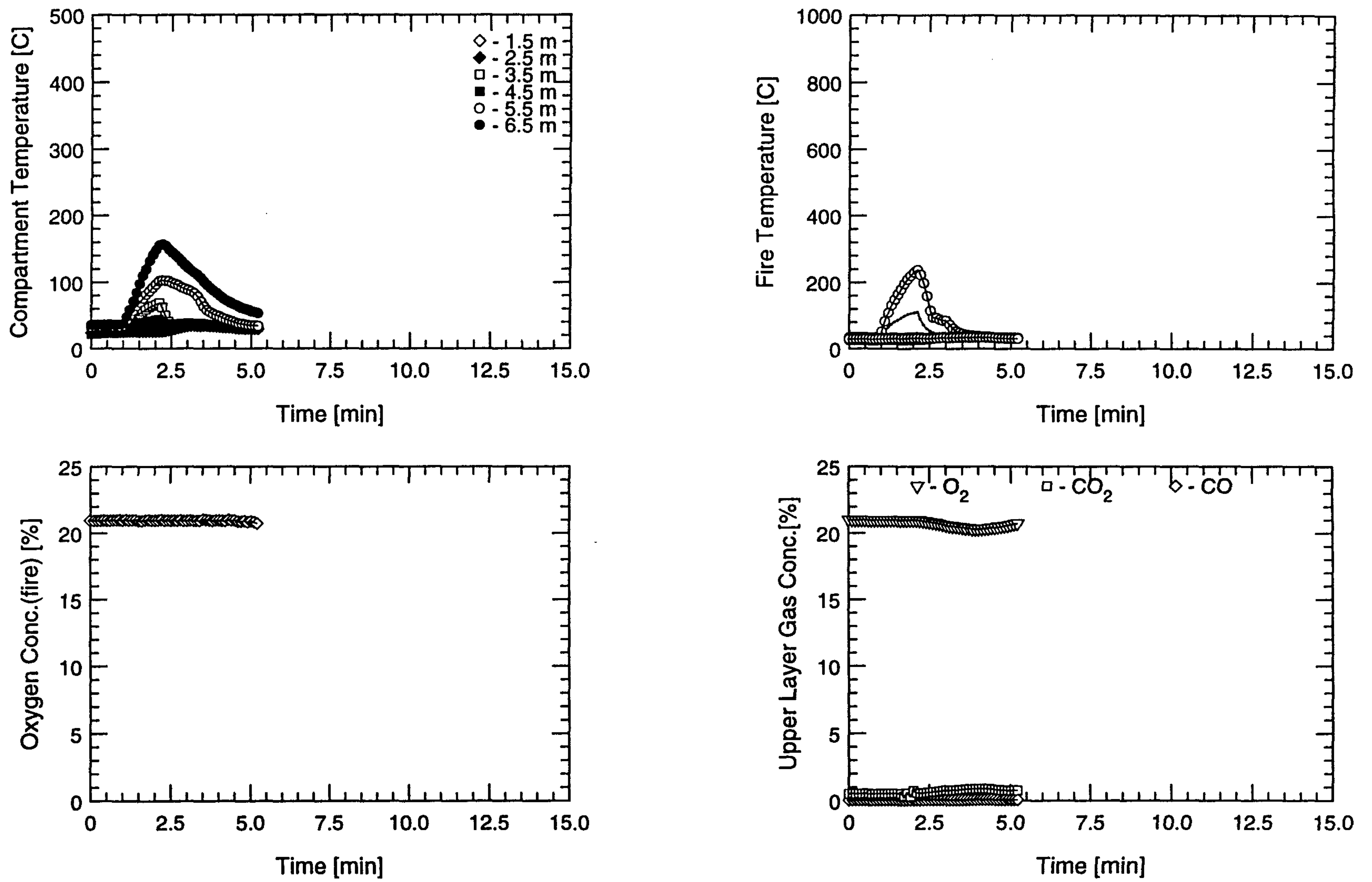


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #53

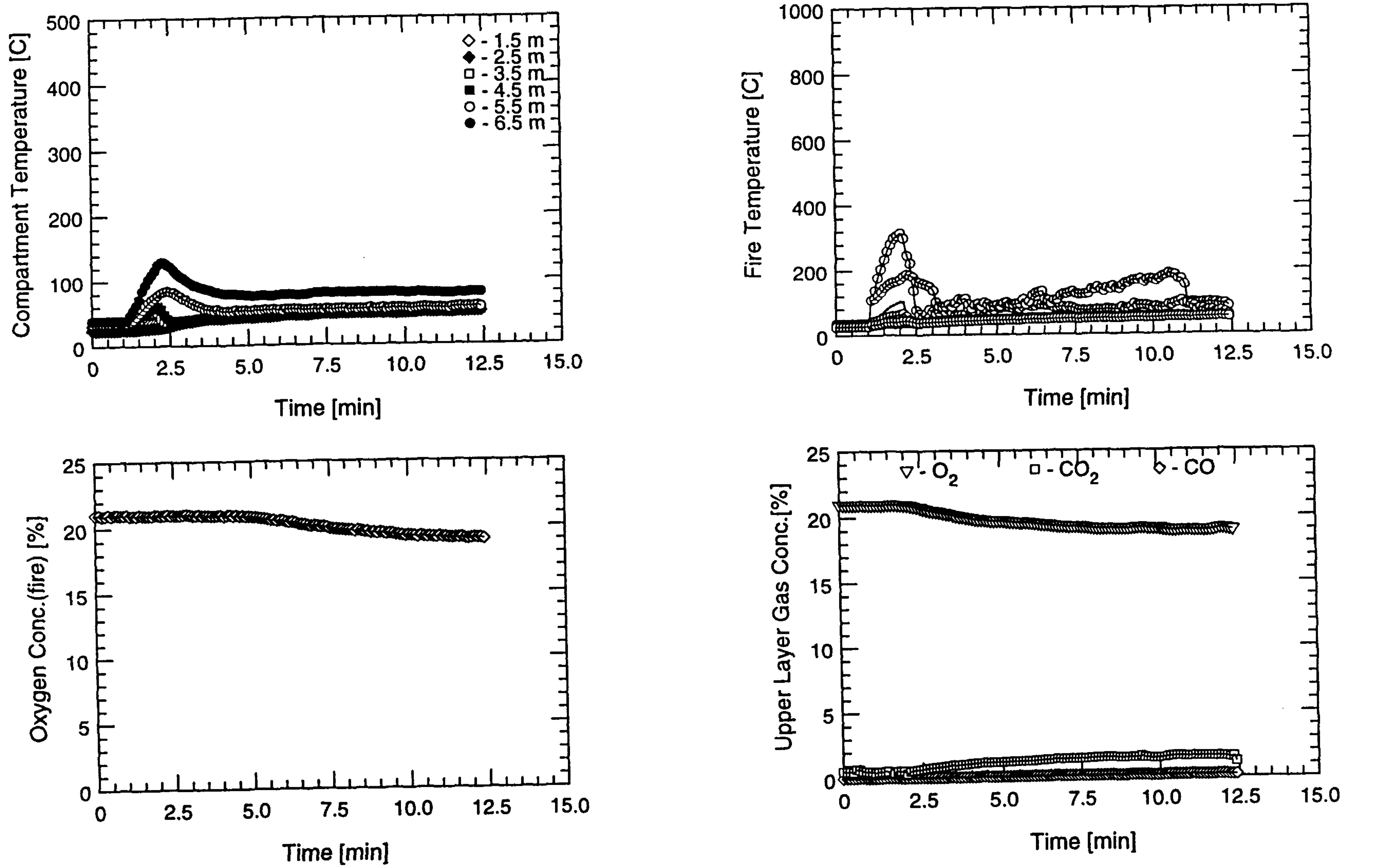

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #54



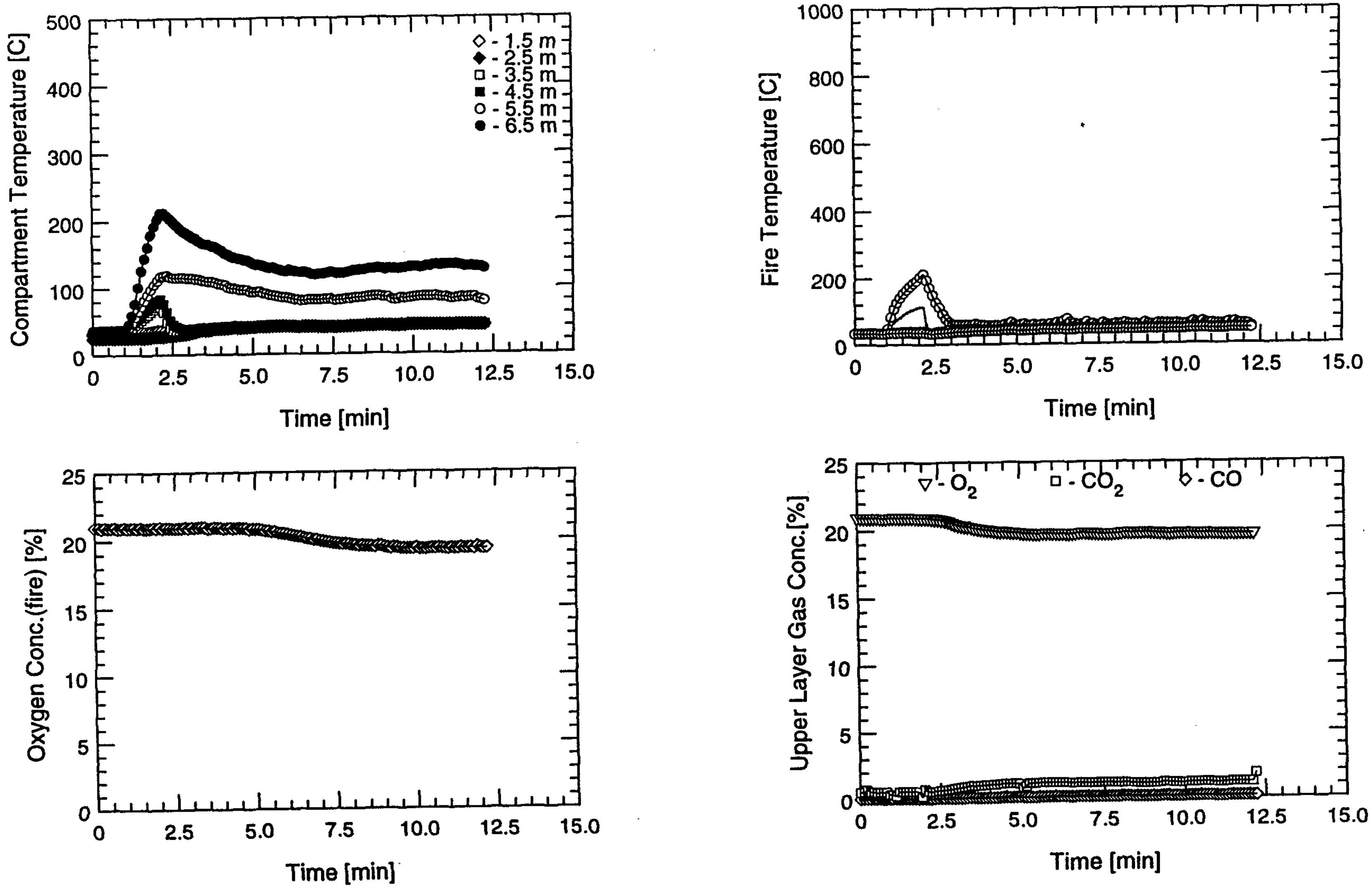
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #55

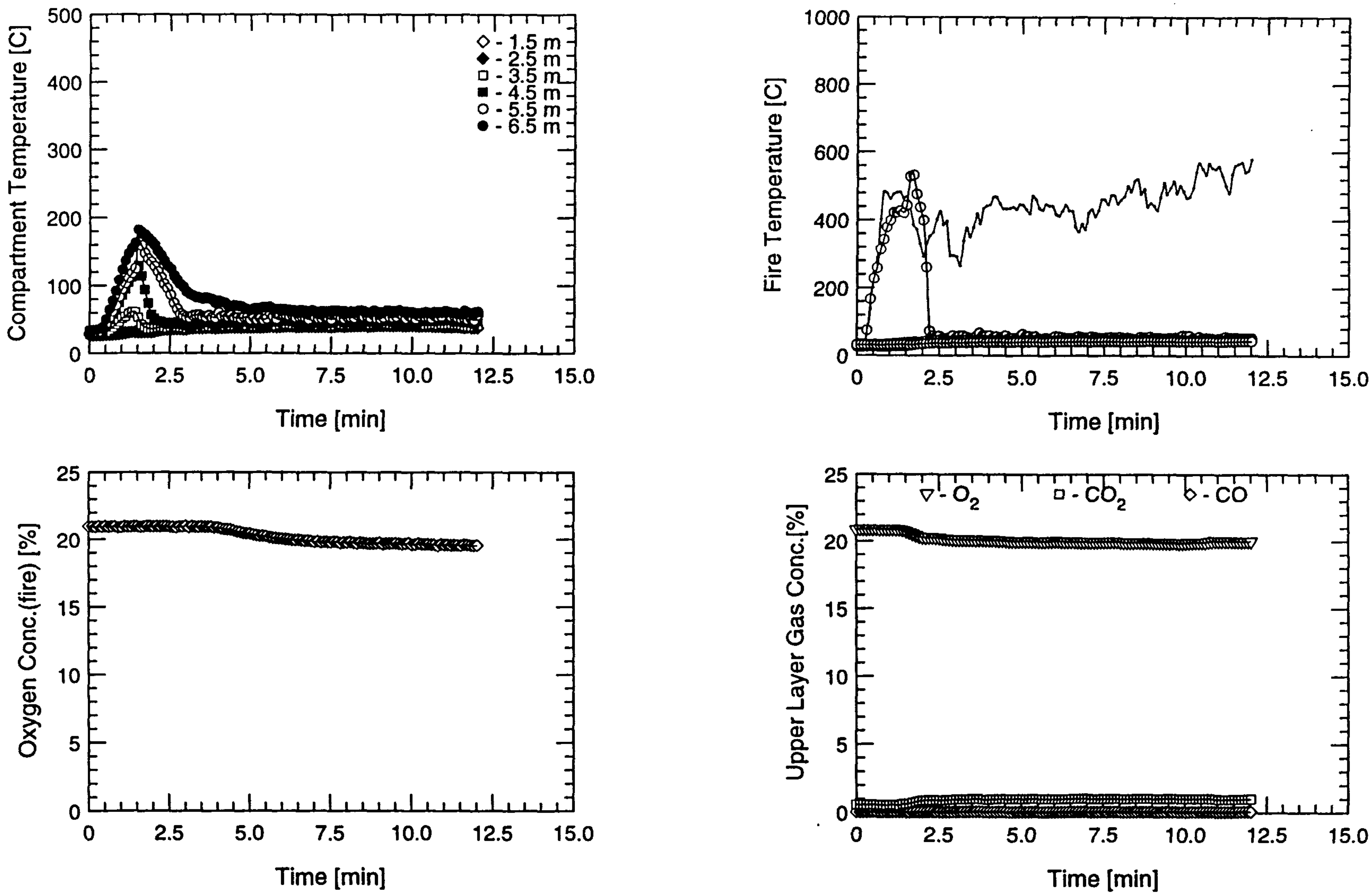


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

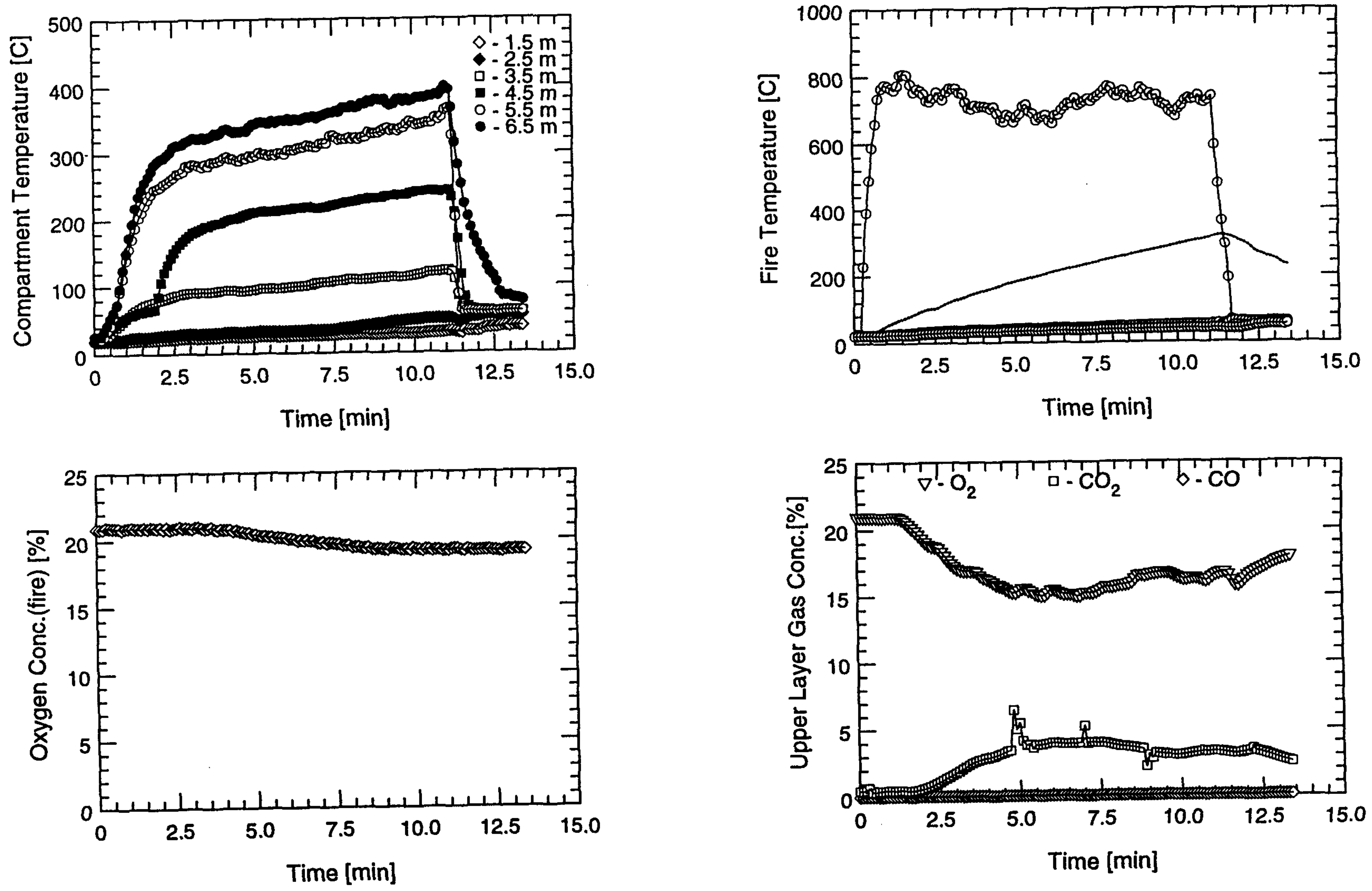
Test #56


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O2
□ - CO2
◇ - CO

Test #57

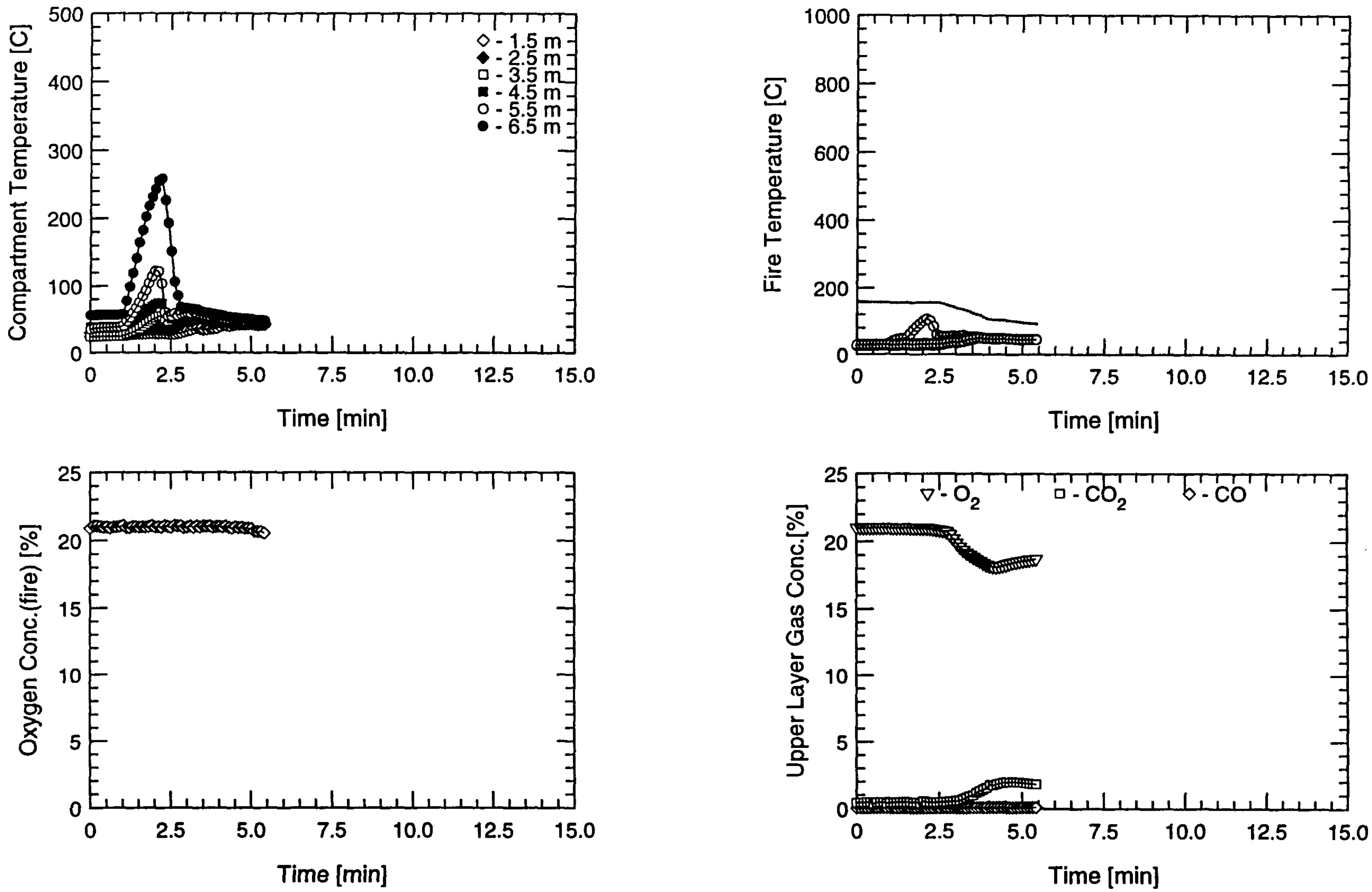

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #58

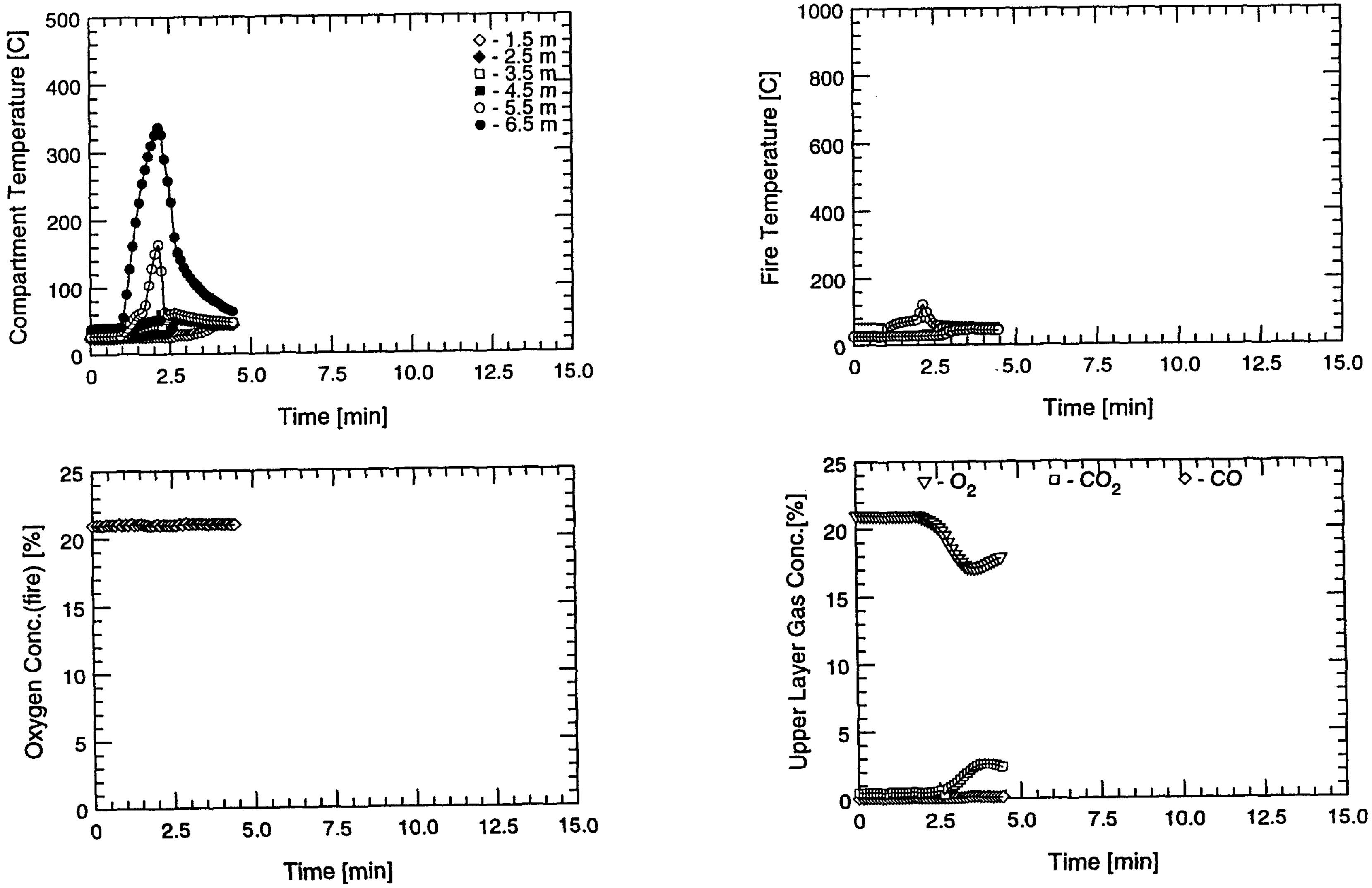


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #59

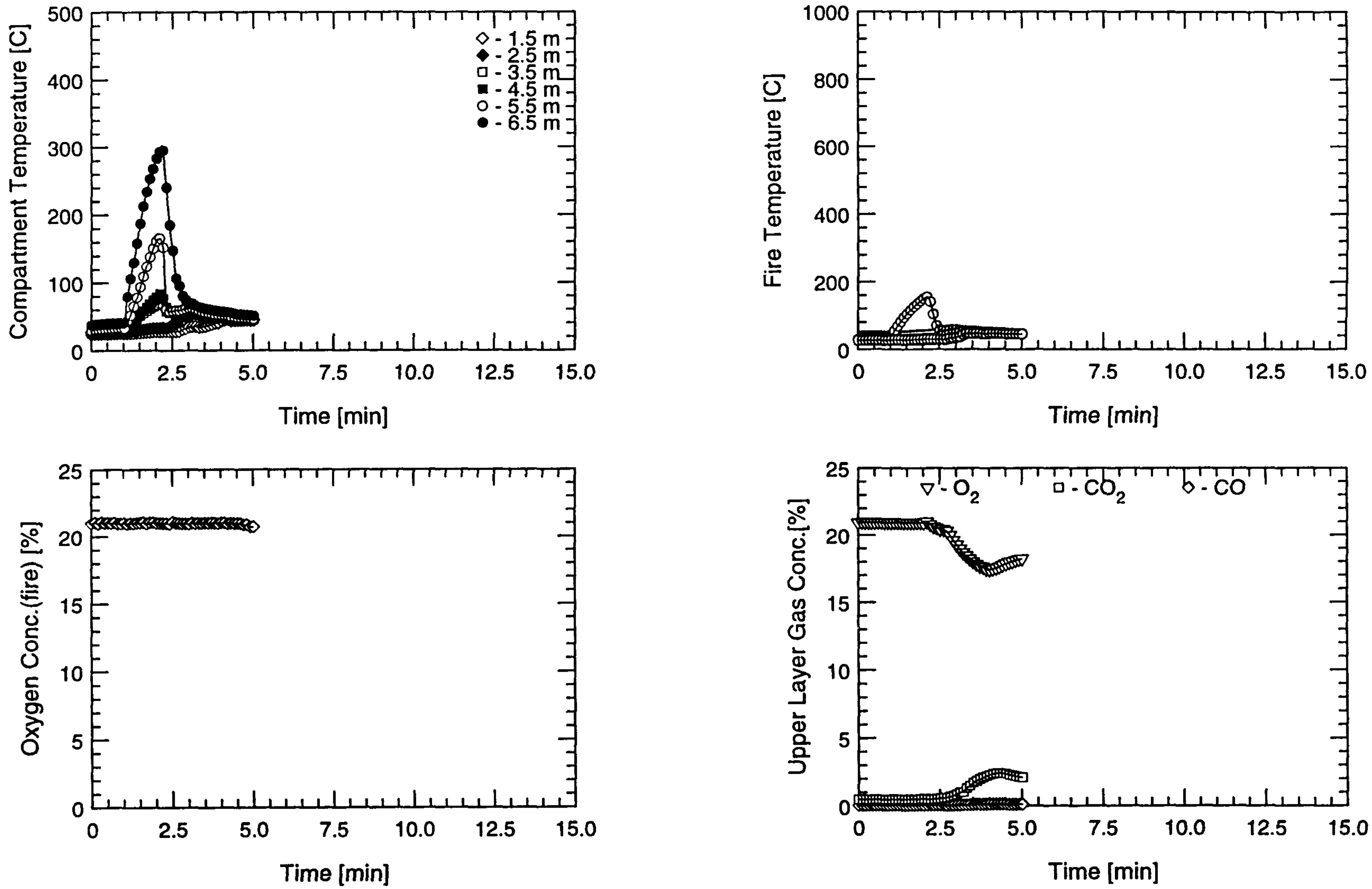

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Oxygen Conc.(fire) [%]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #60



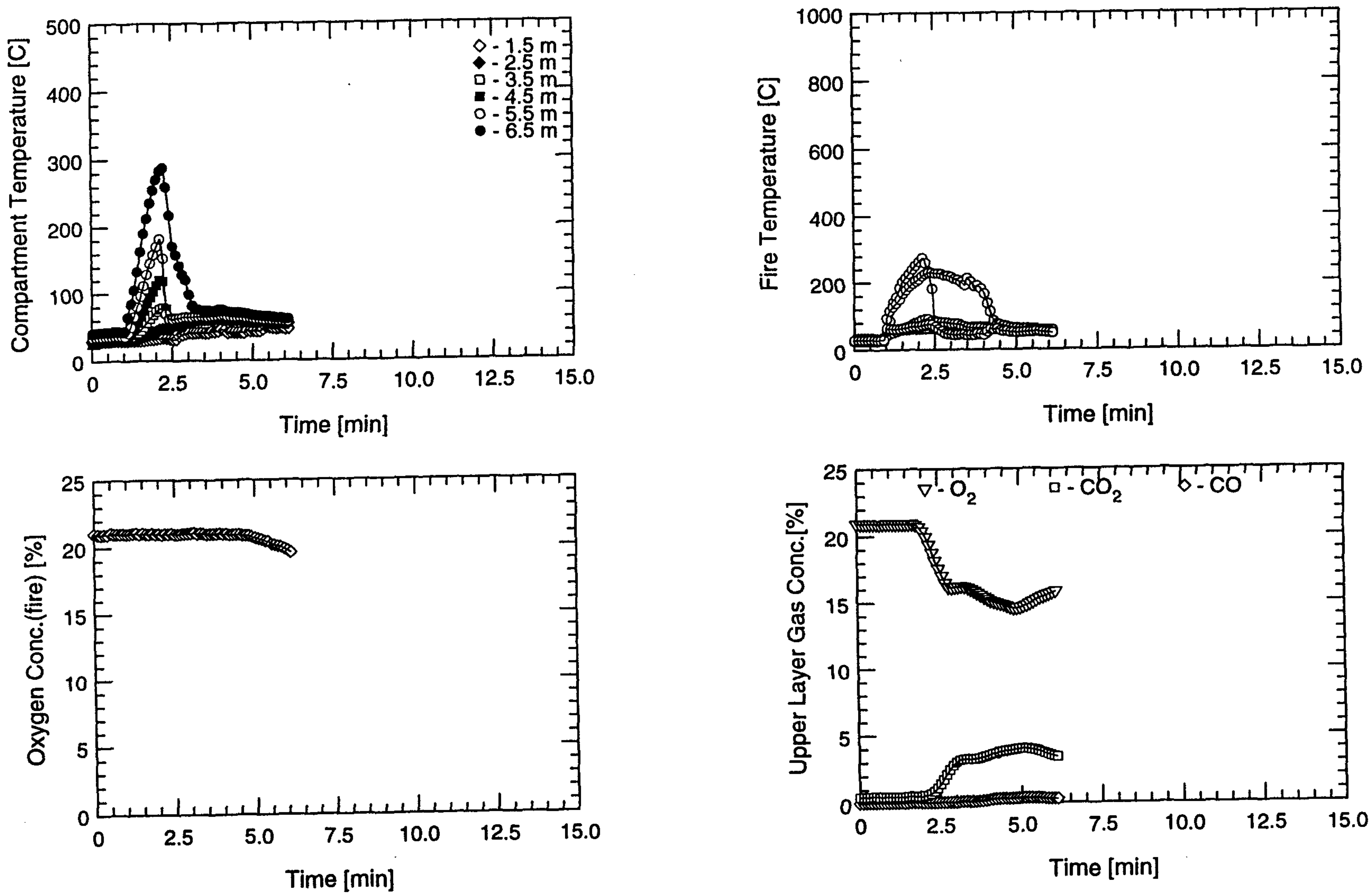
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #61



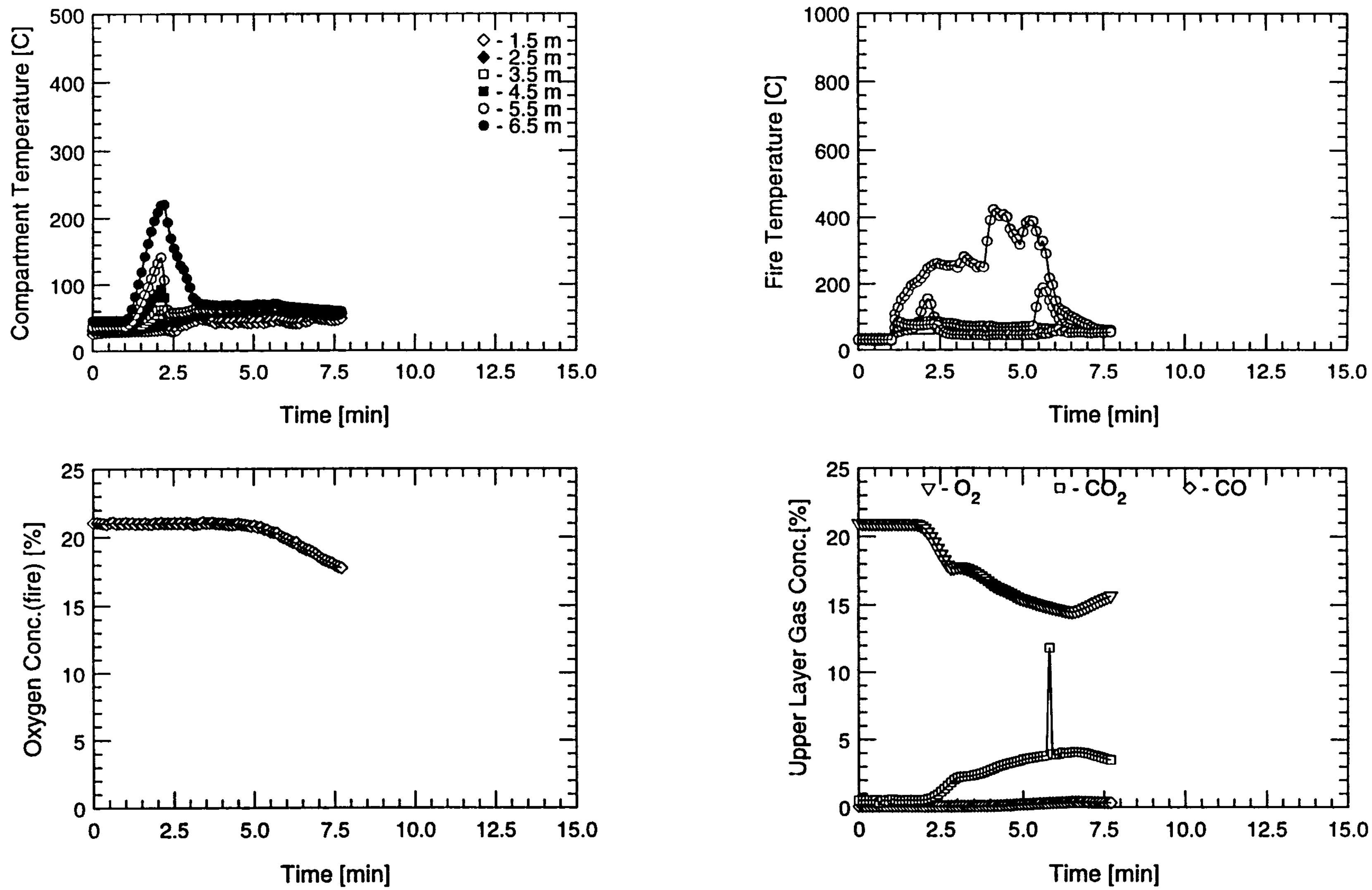
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #62

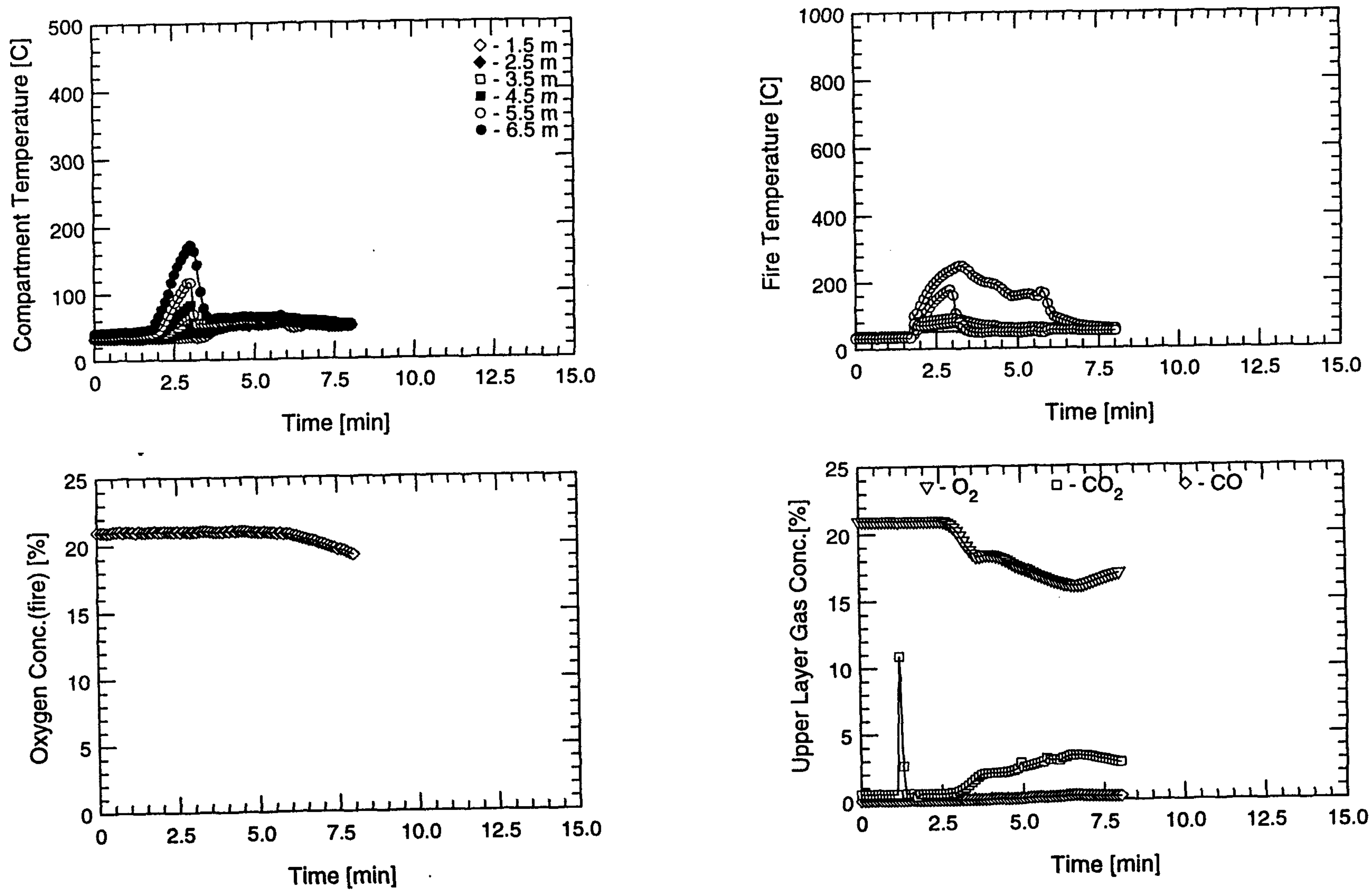


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #63

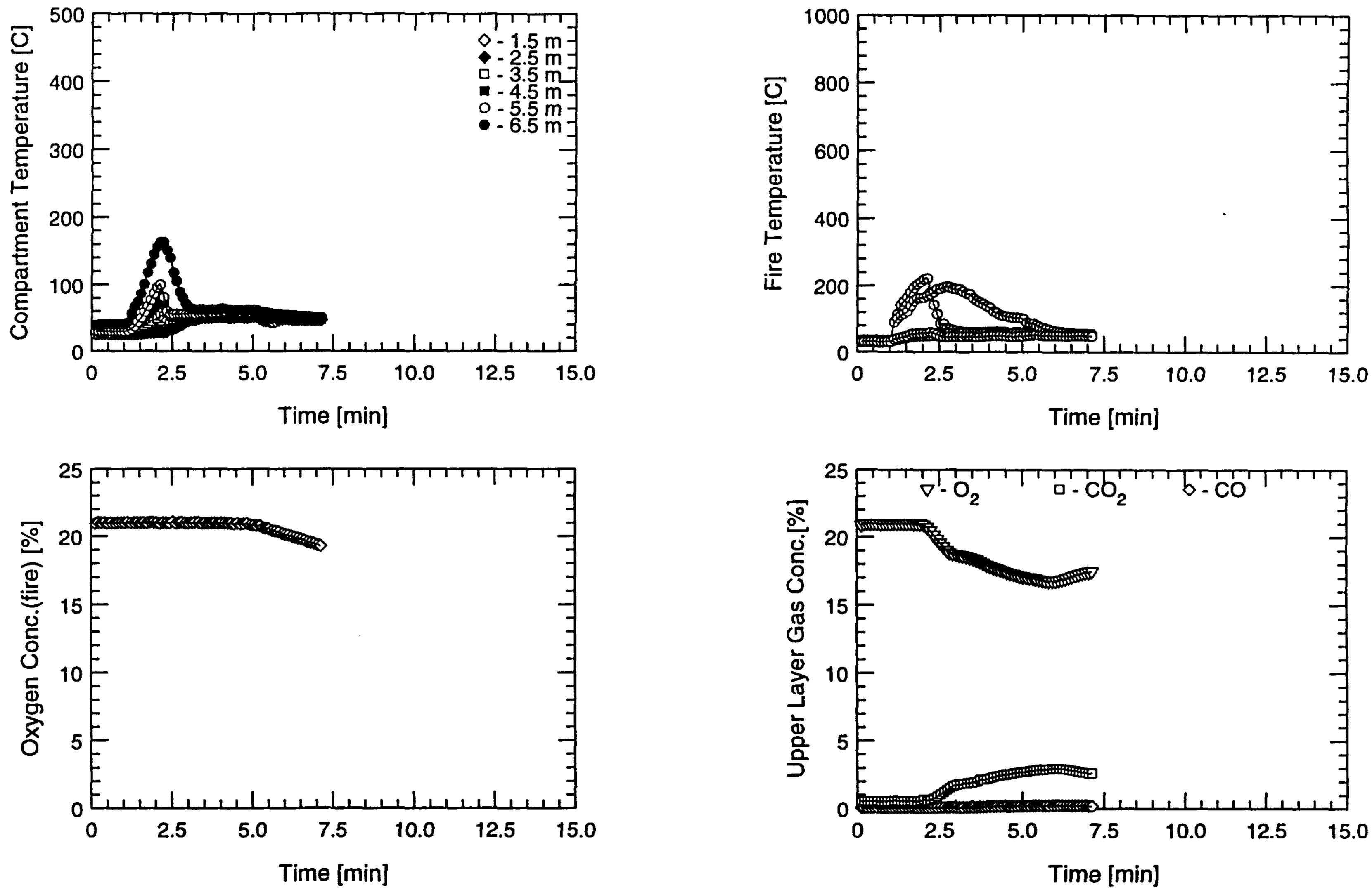

Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #64

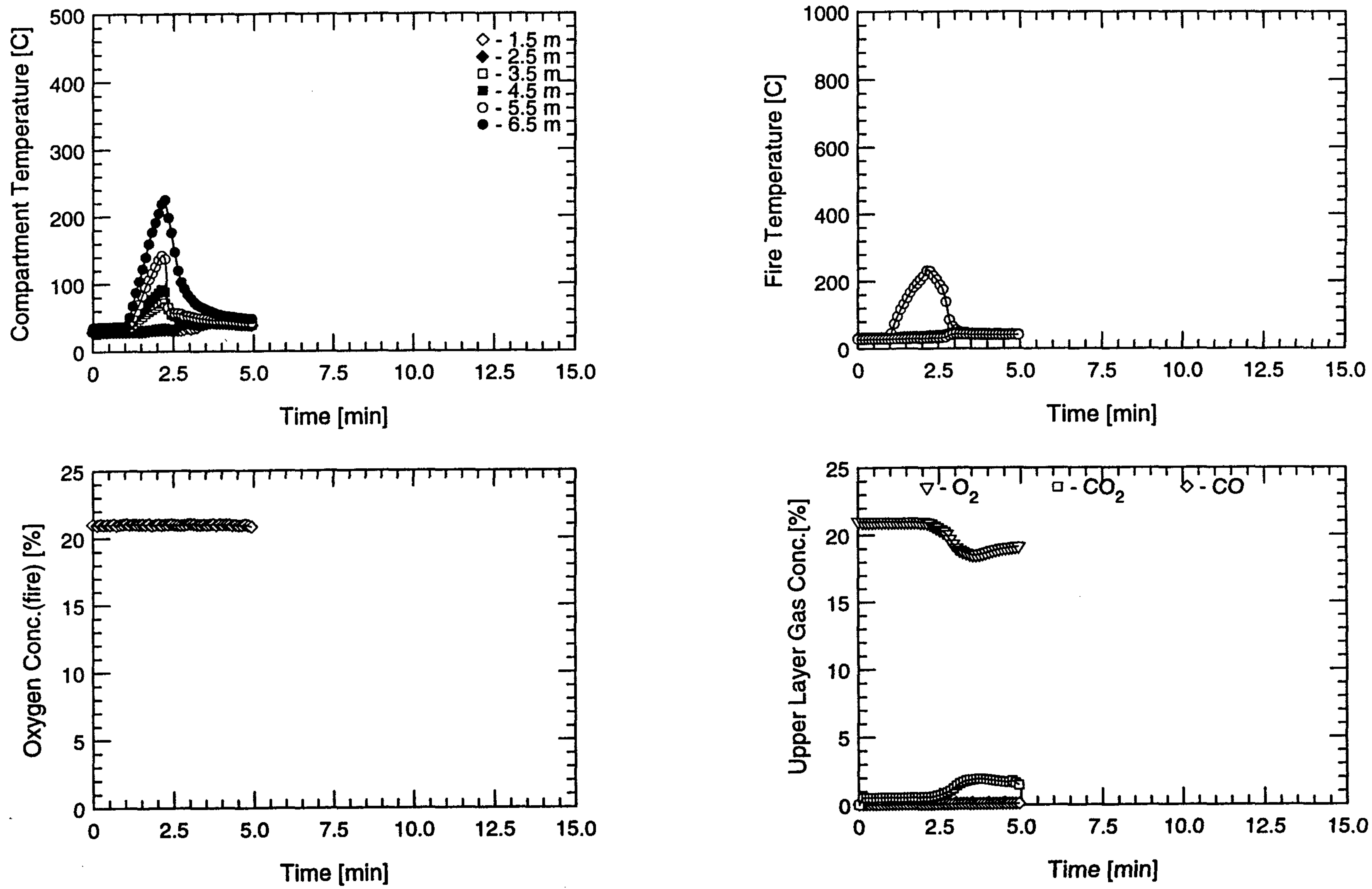


Compartment Temperature [C]
500
400
300
200
100
0
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
- 1.5 m
- 2.5 m
- 3.5 m
- 4.5 m
- 5.5 m
- 6.5 m
Fire Temperature [C]
1000
800
600
400
200
0
Oxygen Conc.(fire) [%]
25
20
15
10
5
Upper Layer Gas Conc.[%]
- O_2
- CO_2
- CO

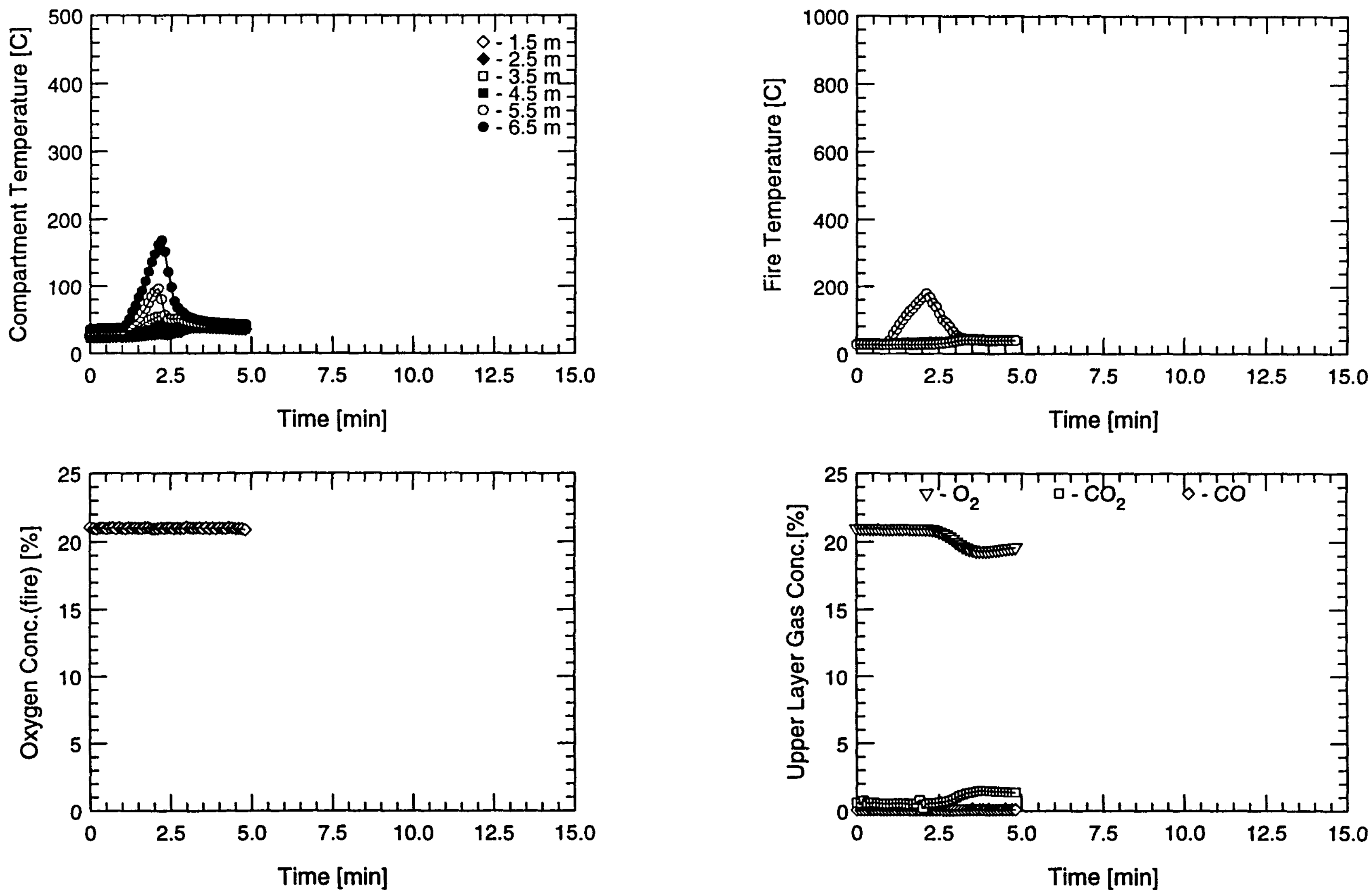
Test #65


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

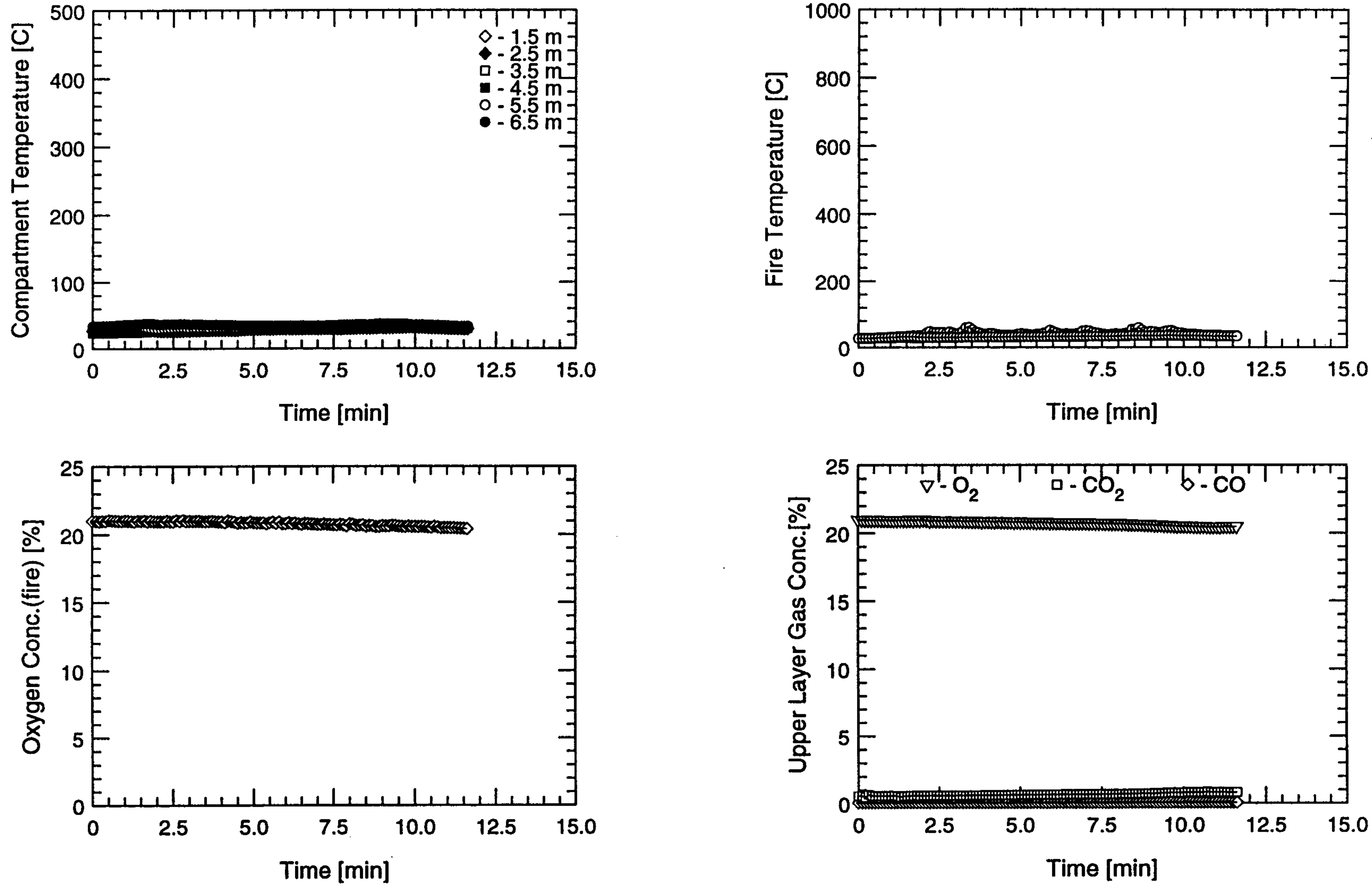
Test #66


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

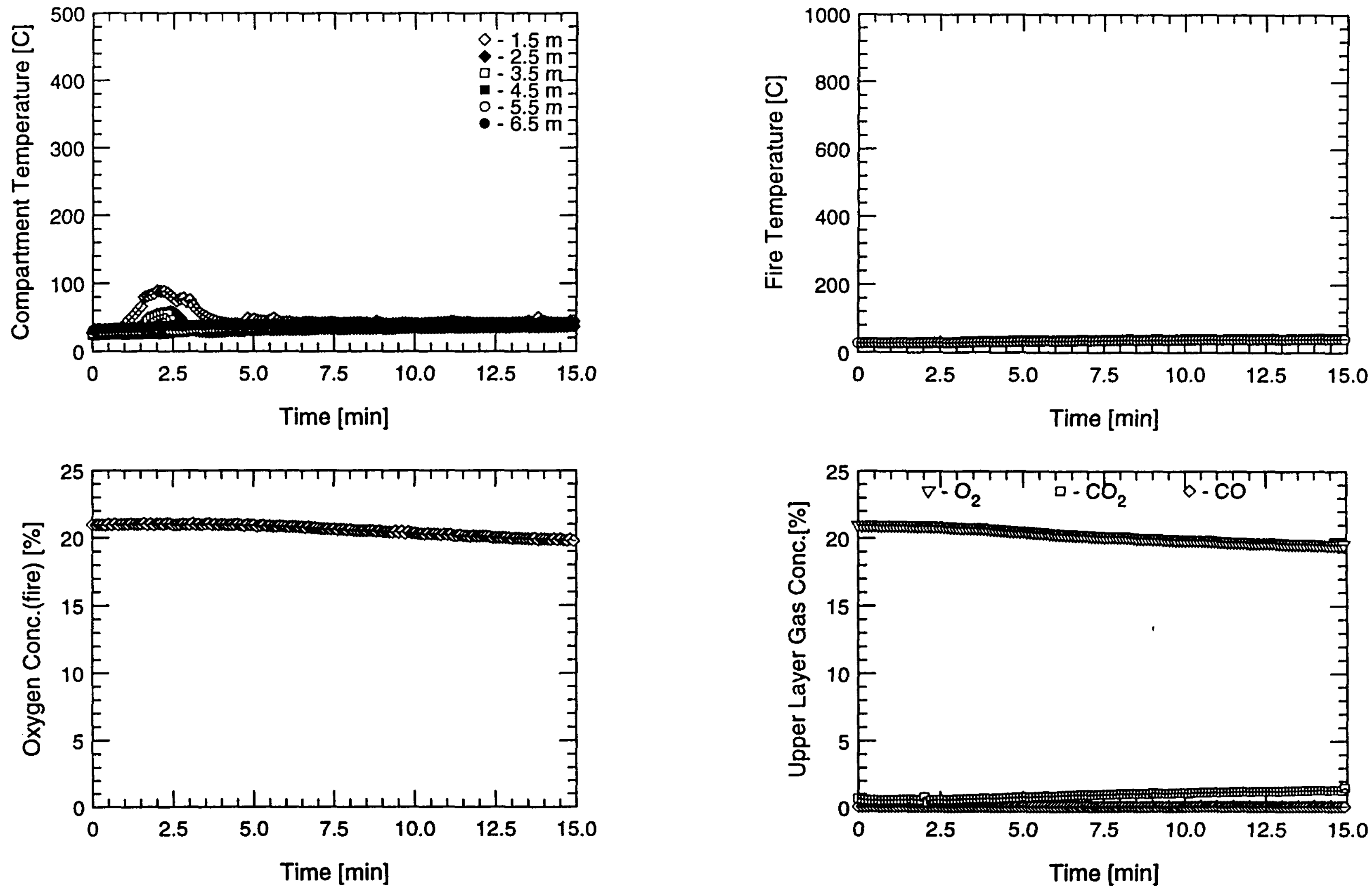
Test #67


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O2
□ - CO2
◇ - CO

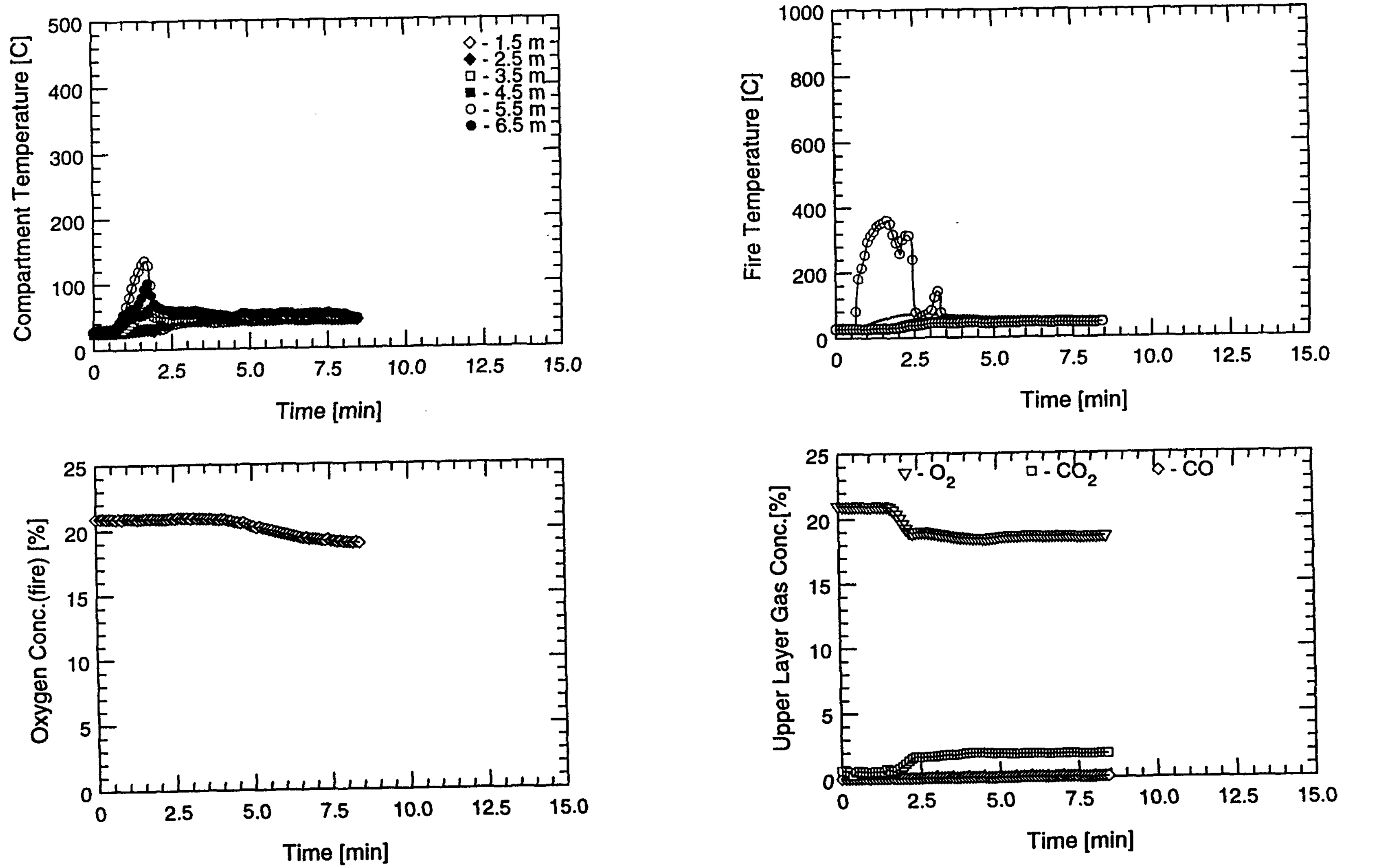
Test #68


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

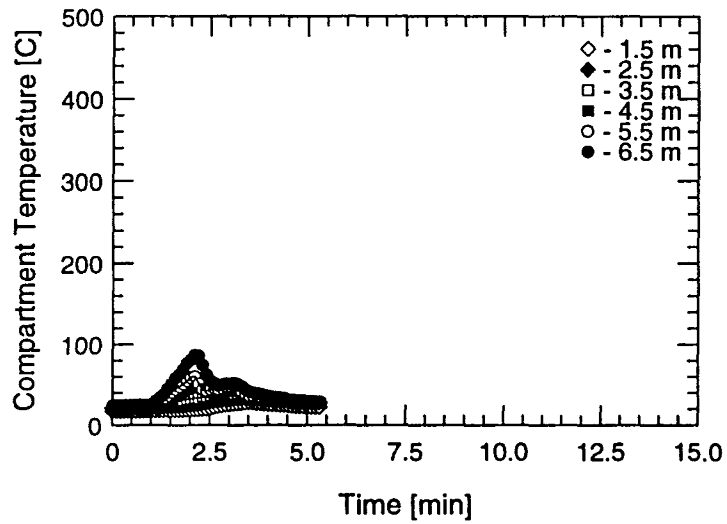
Test #69


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

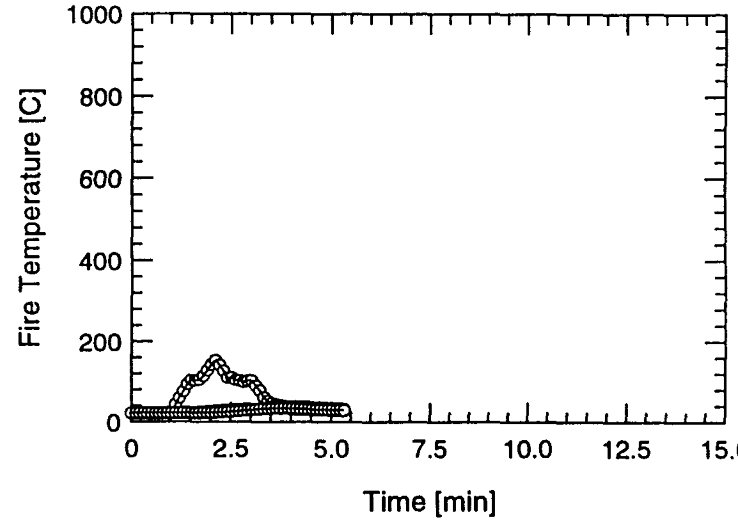
Test #70


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

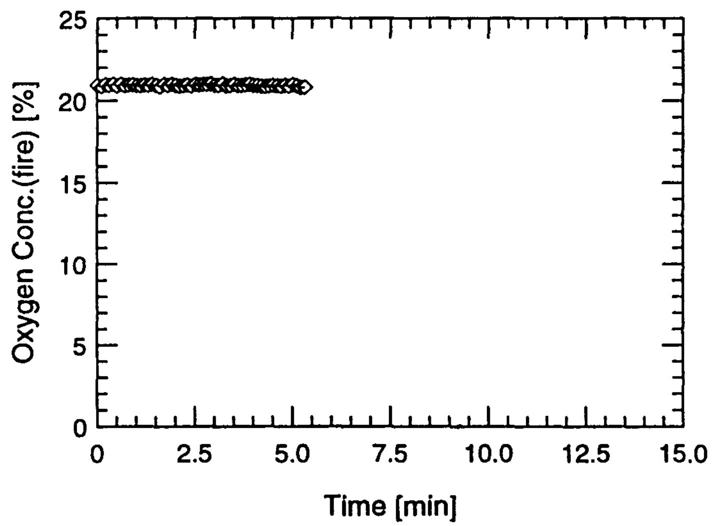
Test #71



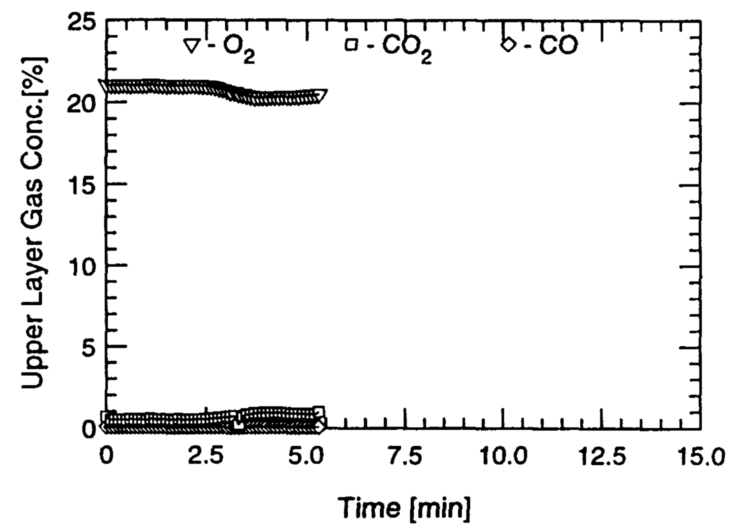
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]



Fire Temperature [C]
1000
800
600
400
200
0
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]

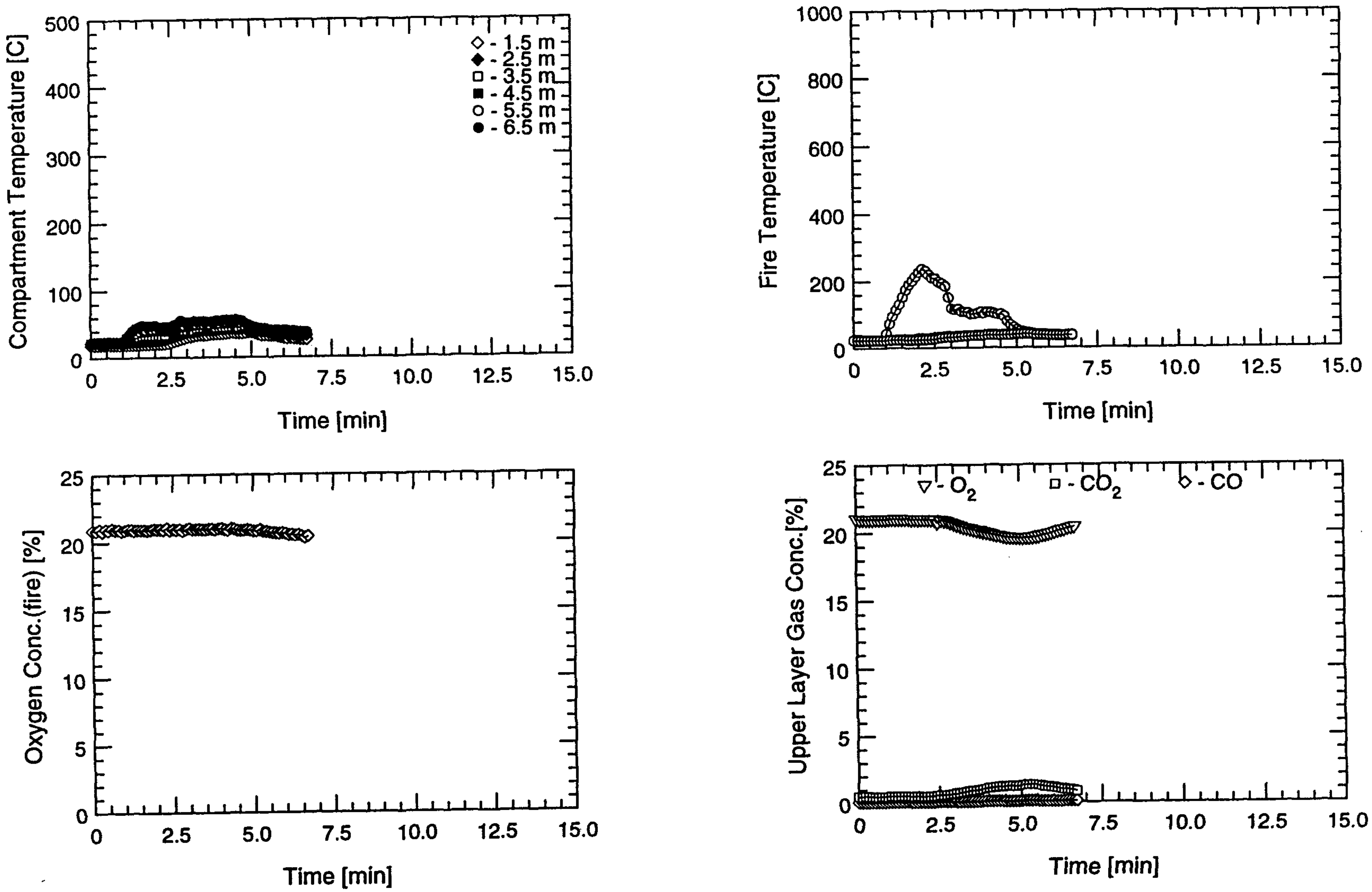


Oxygen Conc.(fire) [%]
25
20
15
10
5
0
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]



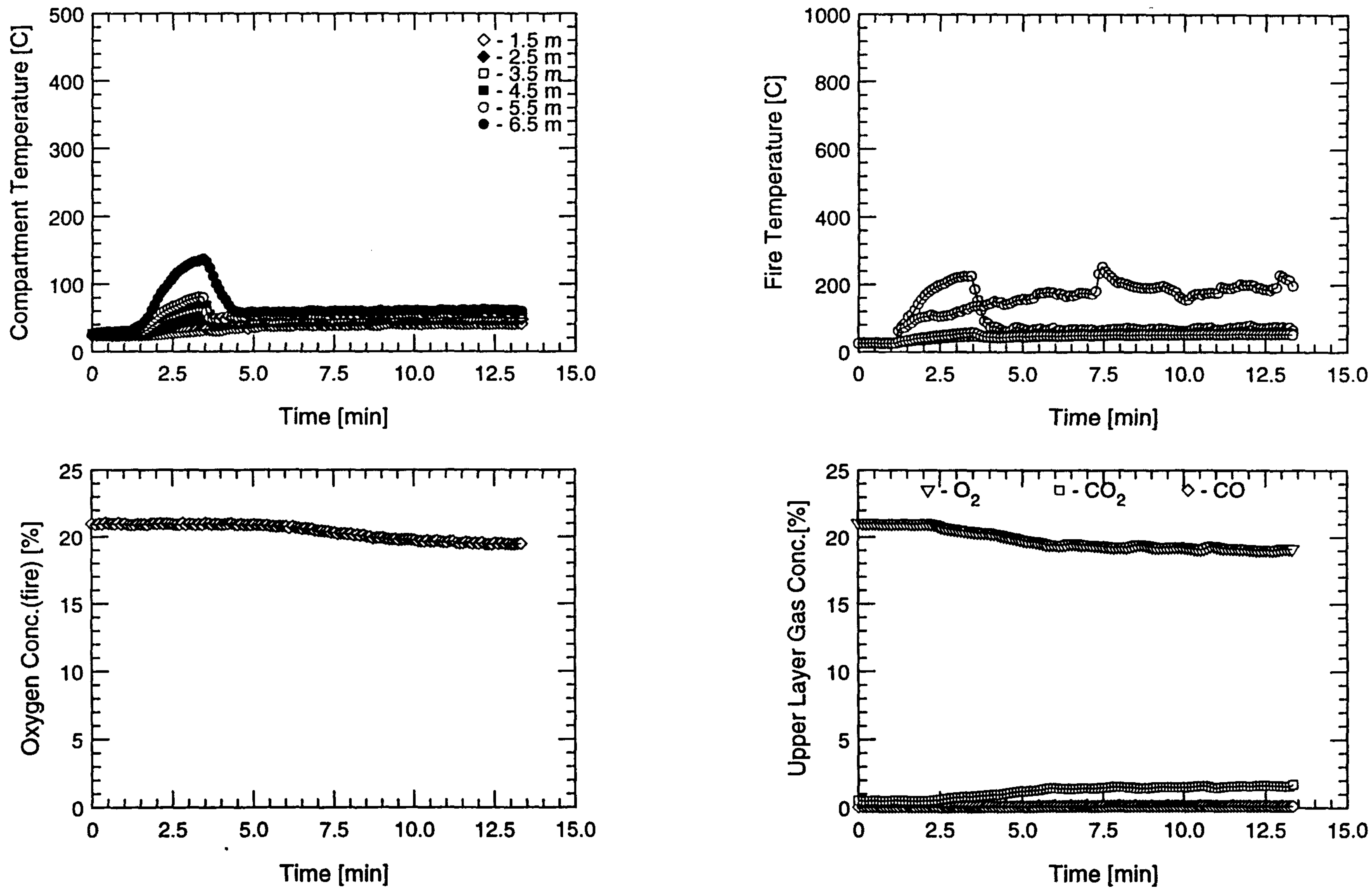
Upper Layer Gas Conc.[%]
25
20
15
10
5
0
▽ - O_2
□ - CO_2
◇ - CO
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]

Test #72



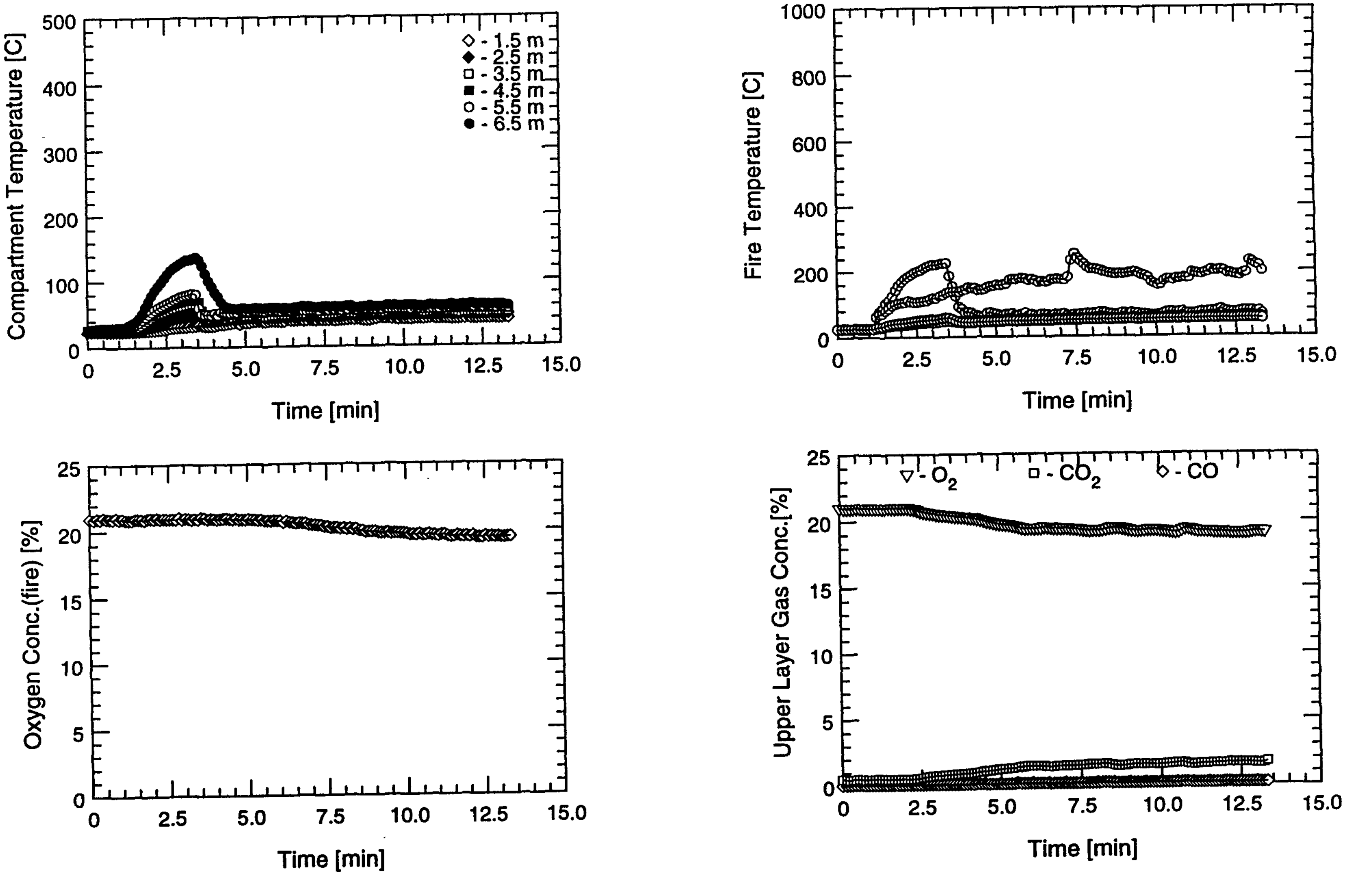
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #73



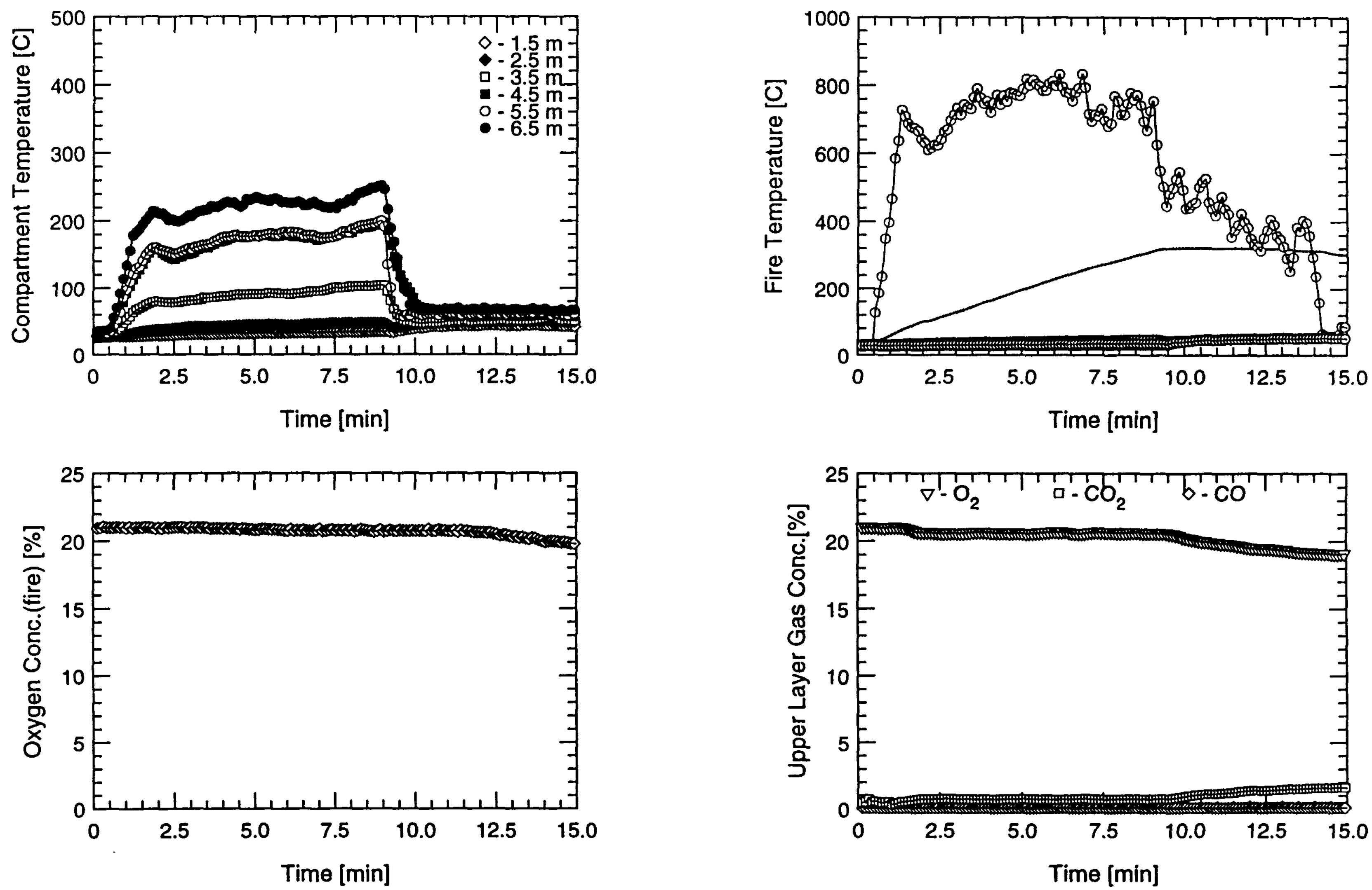
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #74



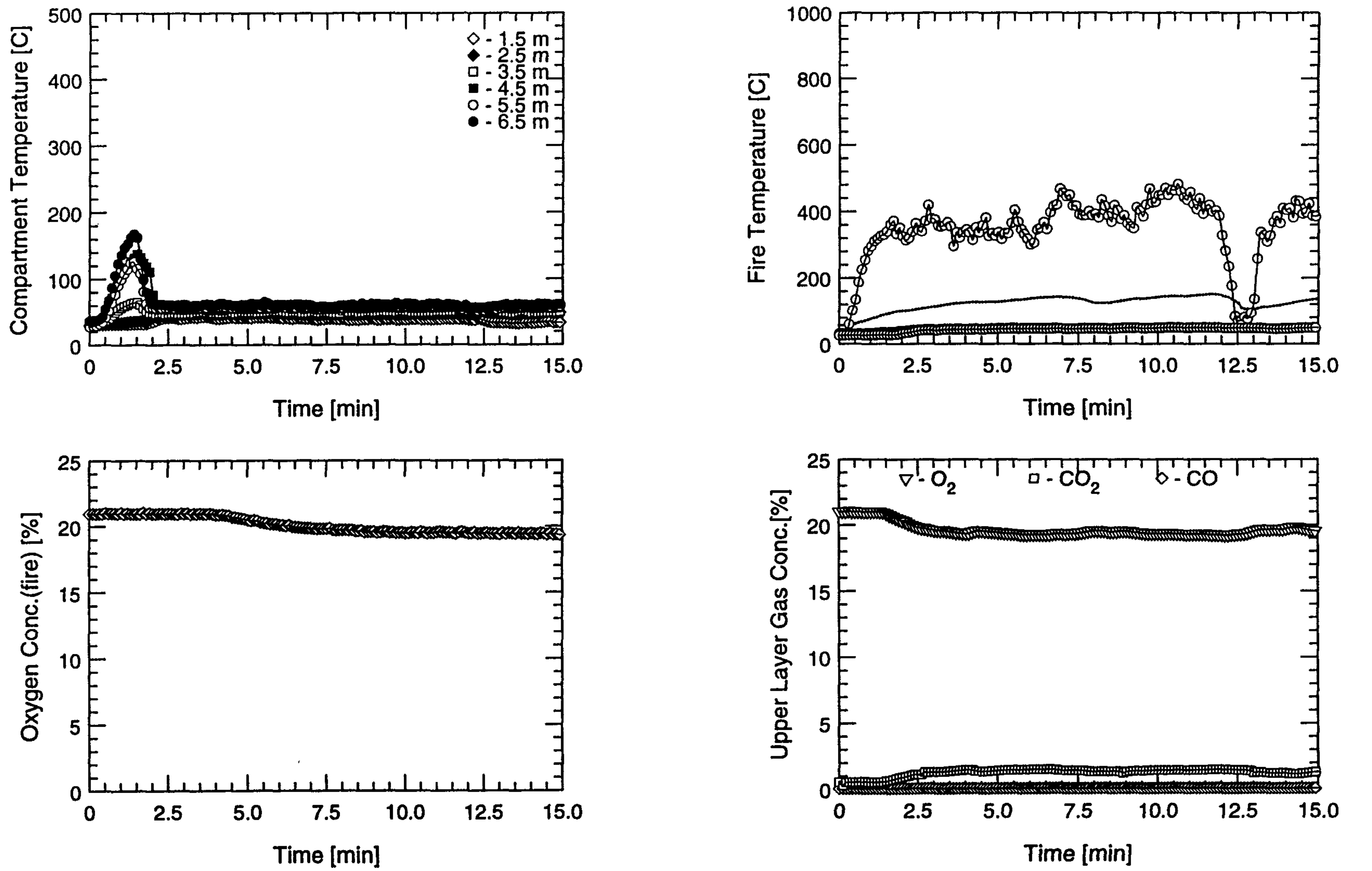
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #75

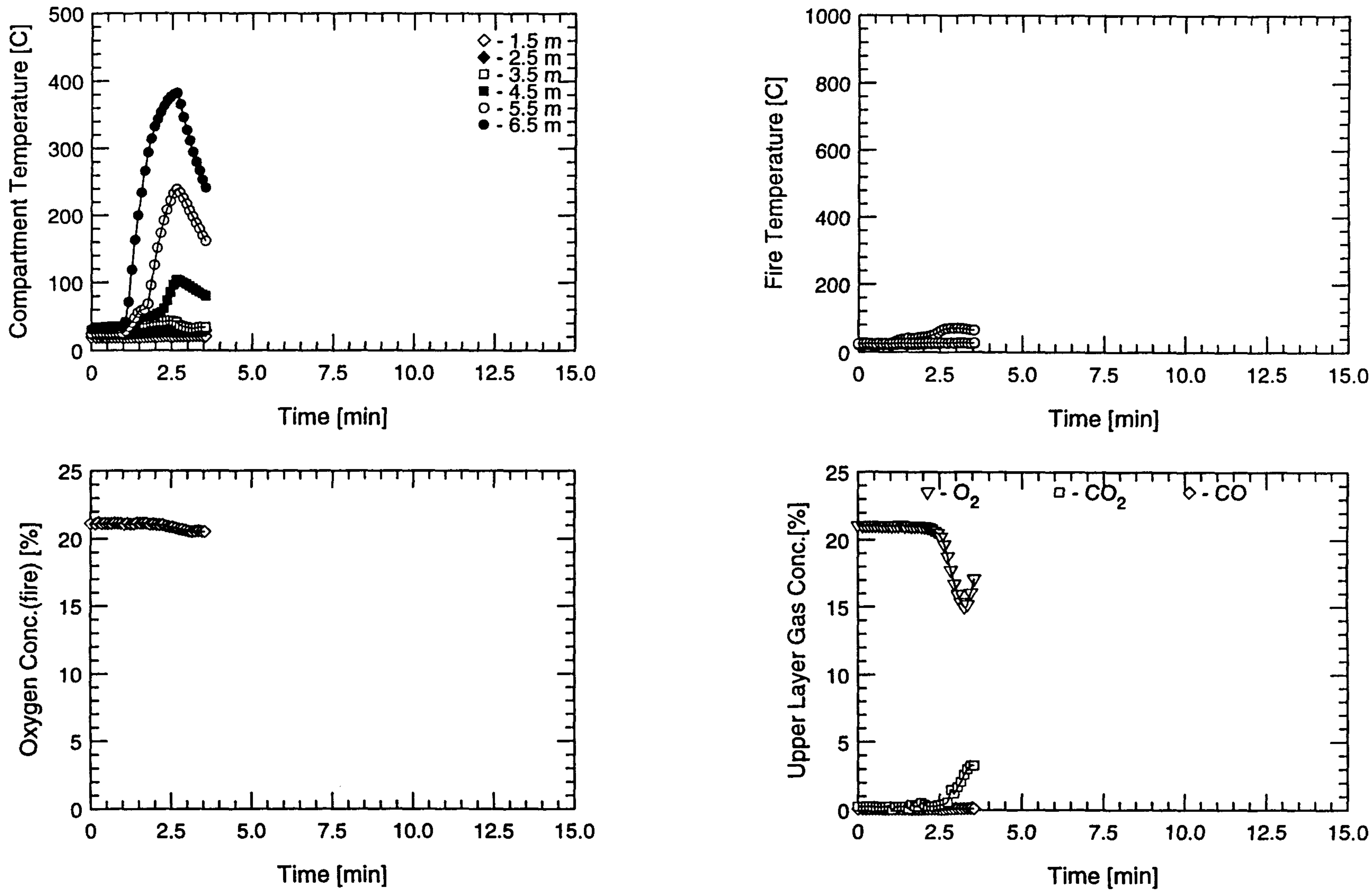


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

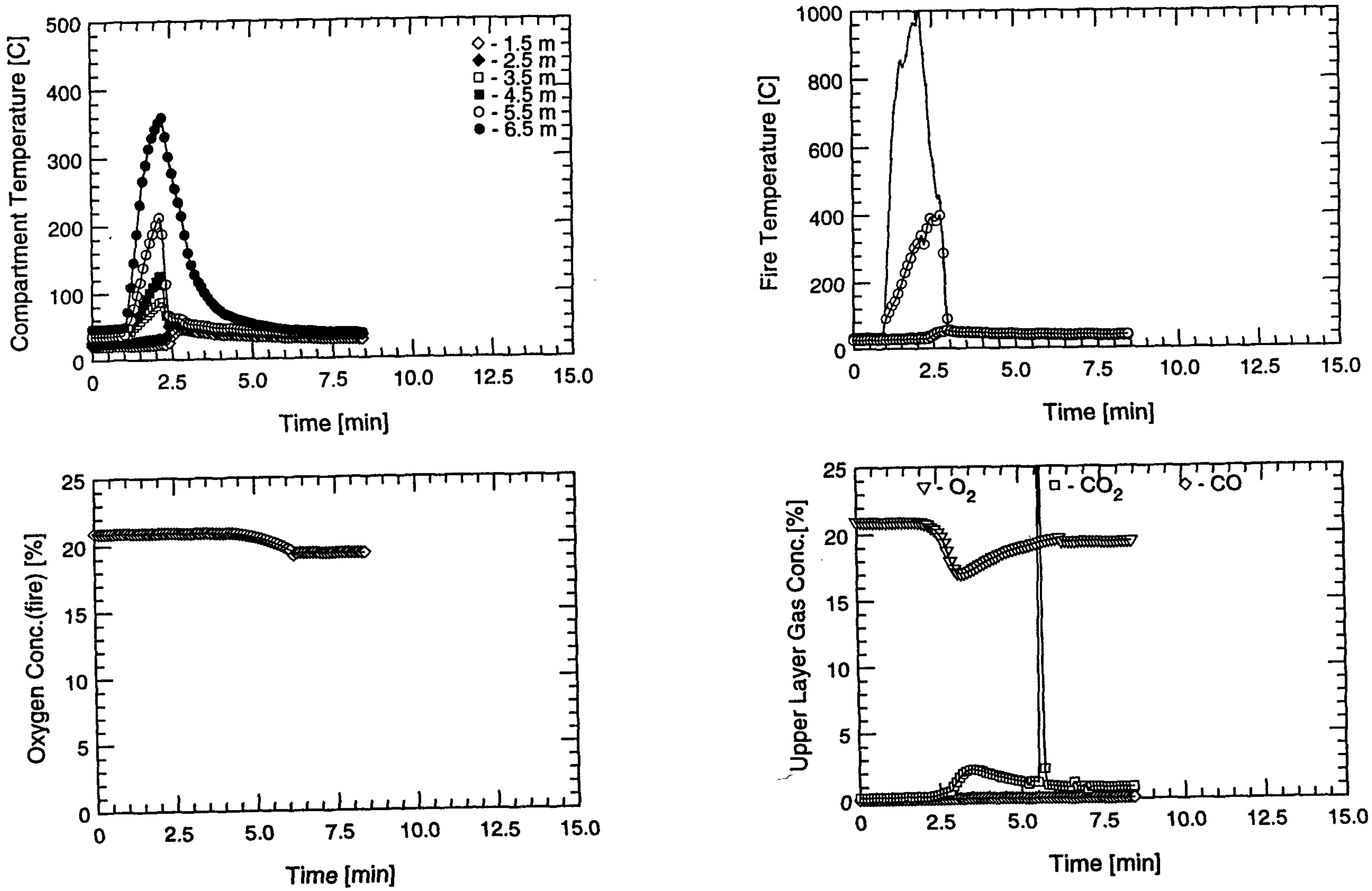
Test #76


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #77

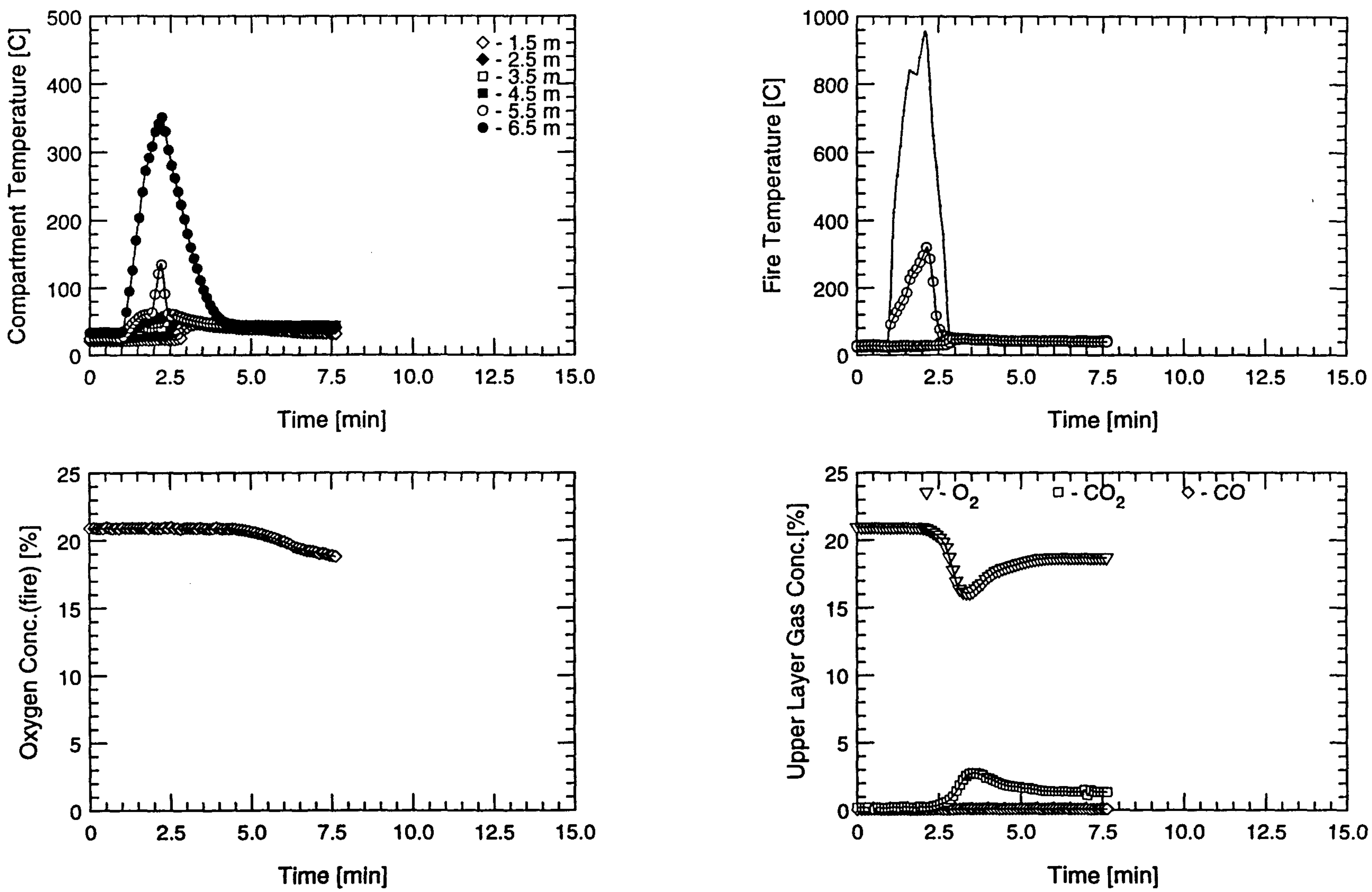

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #78

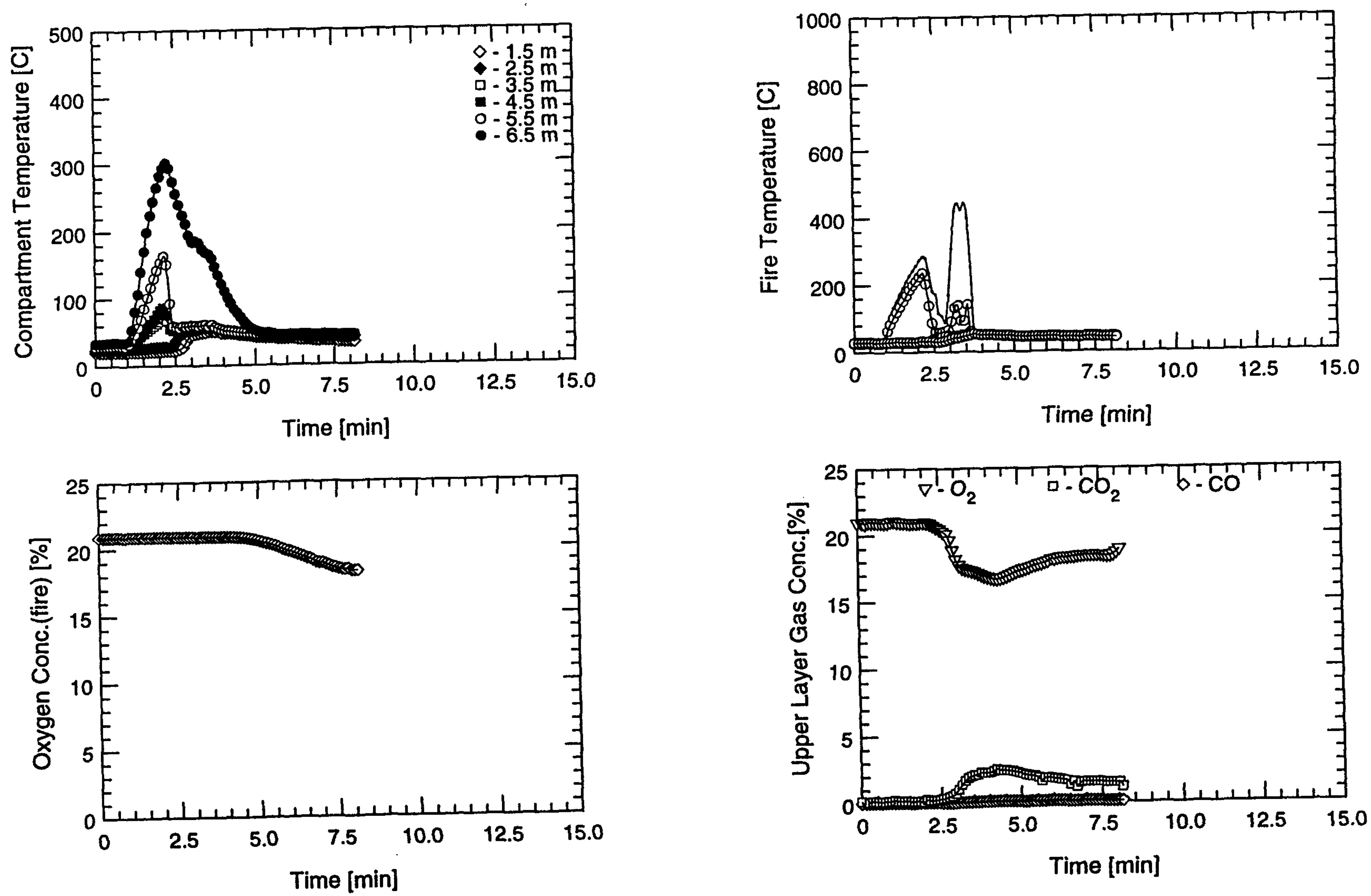


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #79

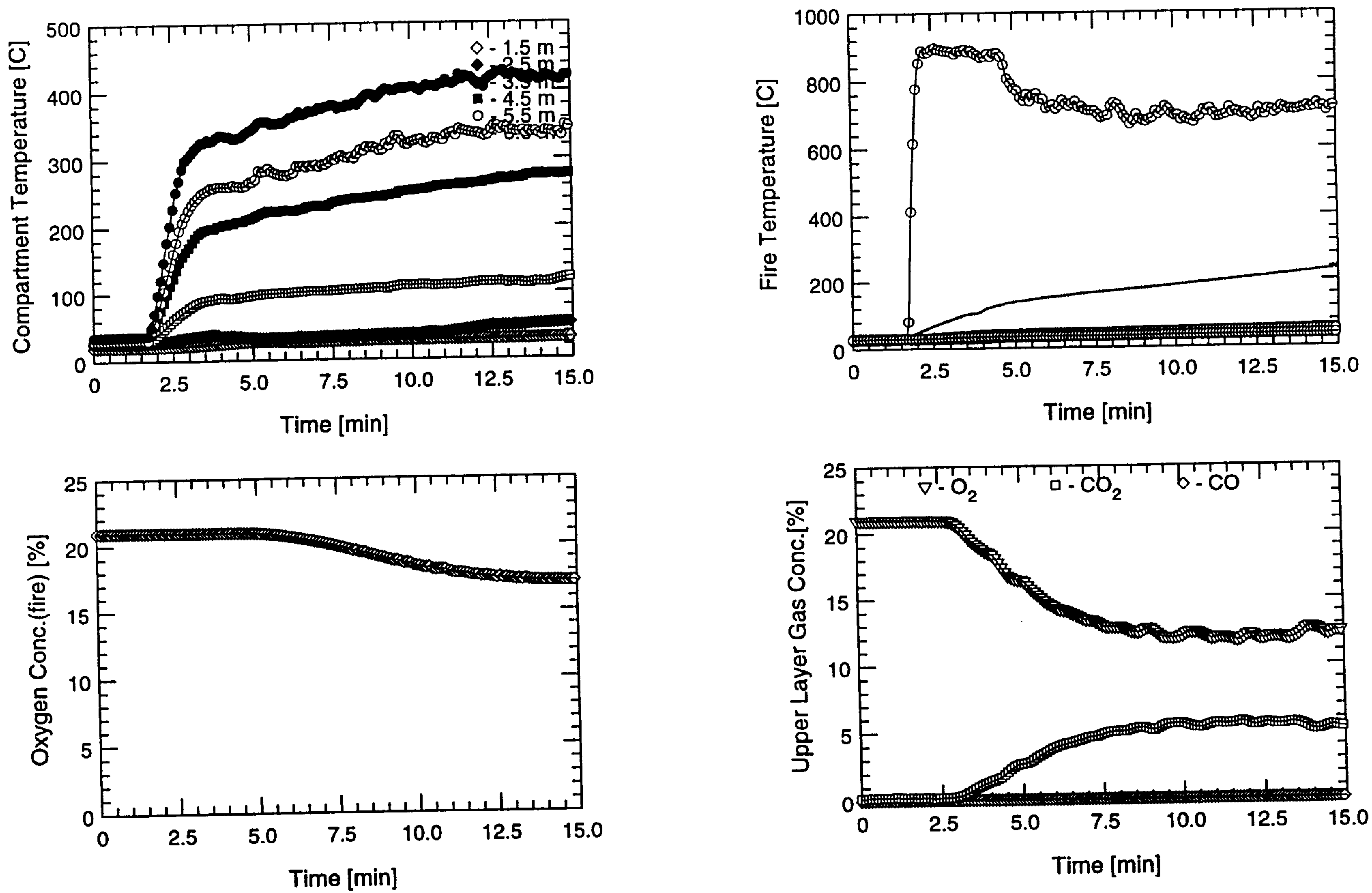

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O2
□ - CO2
◇ - CO

Test #80

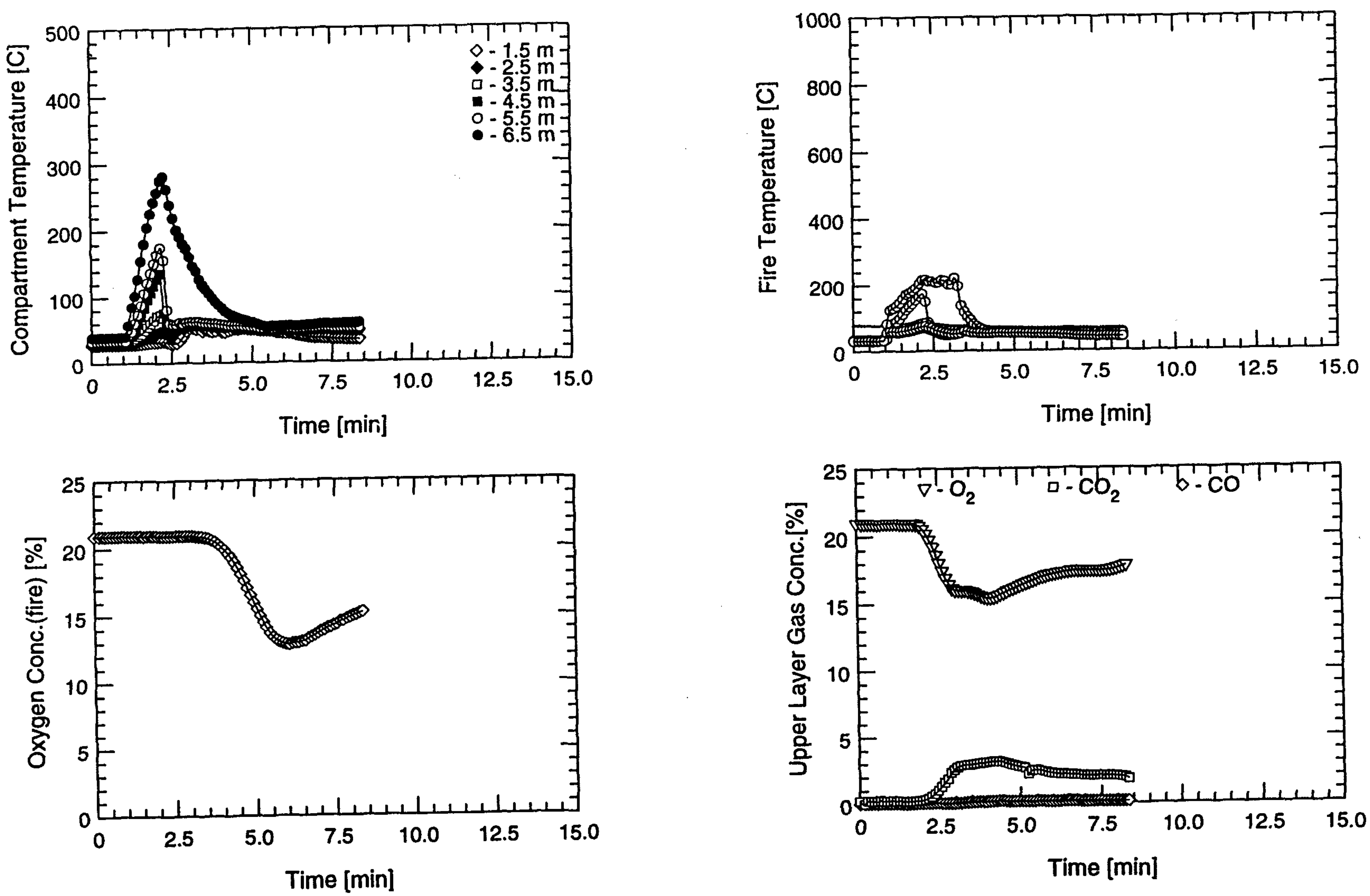


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #81

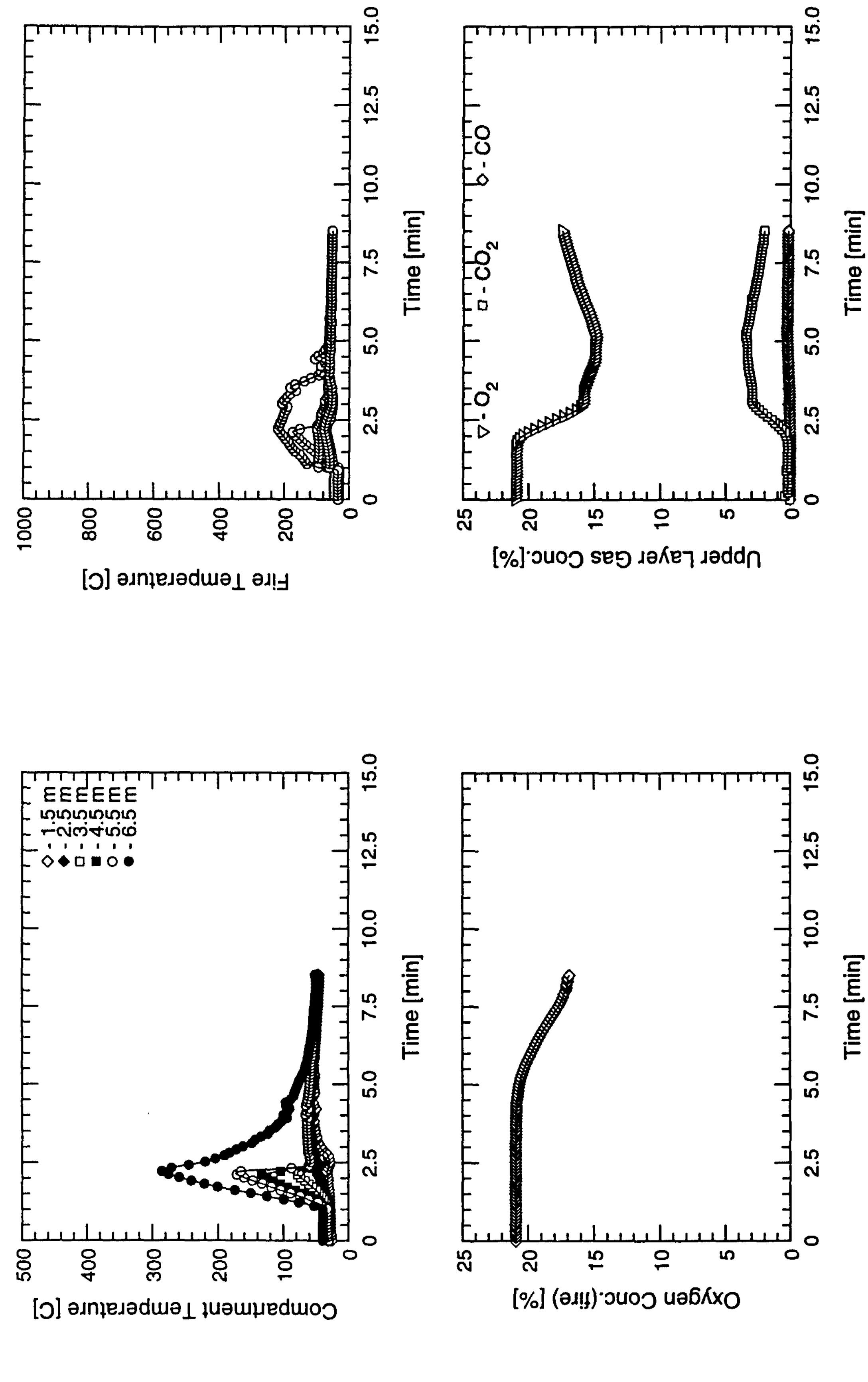

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
■ - 4.5 m
○ - 5.5 m
Fire Temperature [C]
Oxygen Conc.(fire) [%]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #82



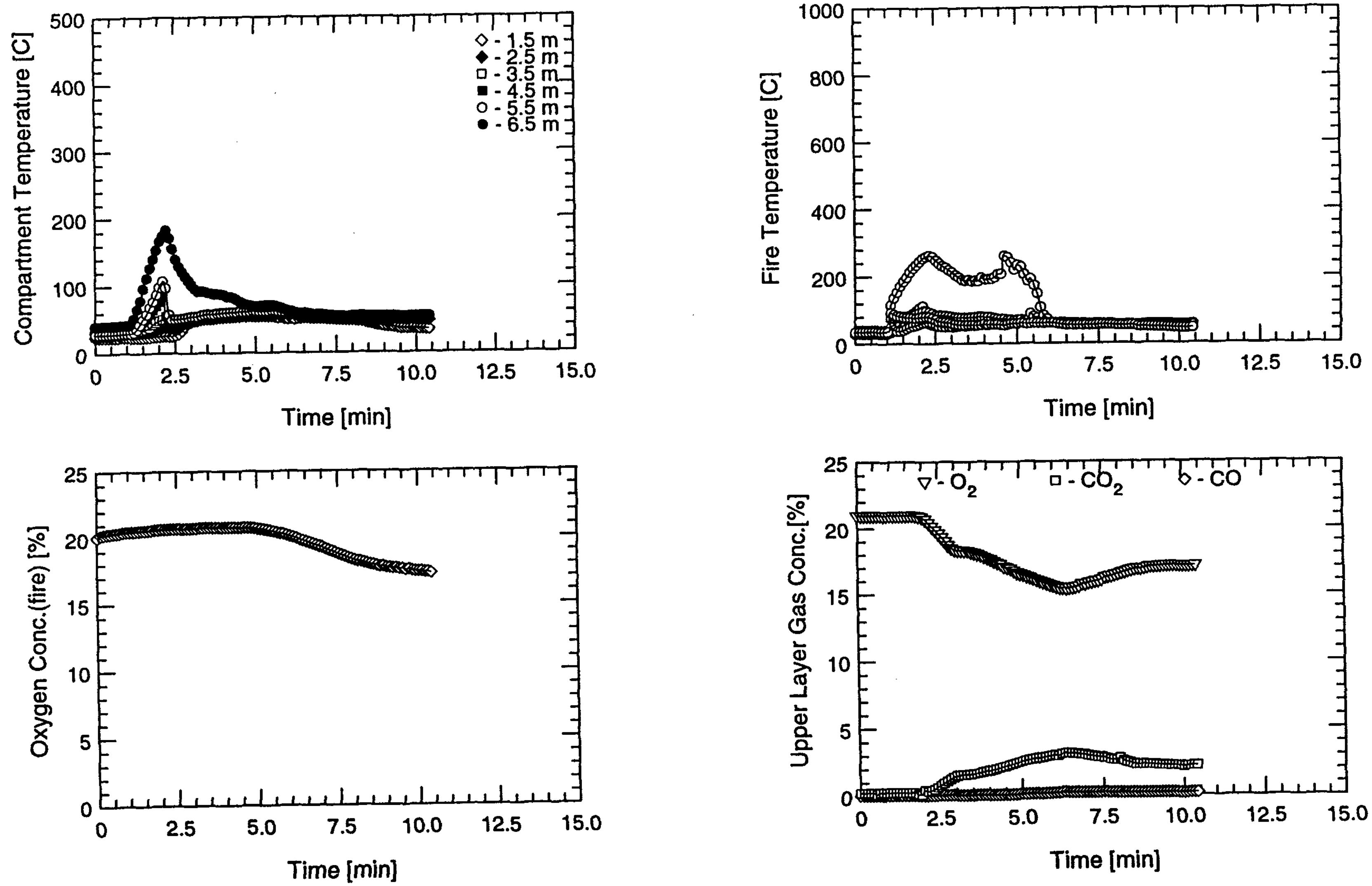
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #83

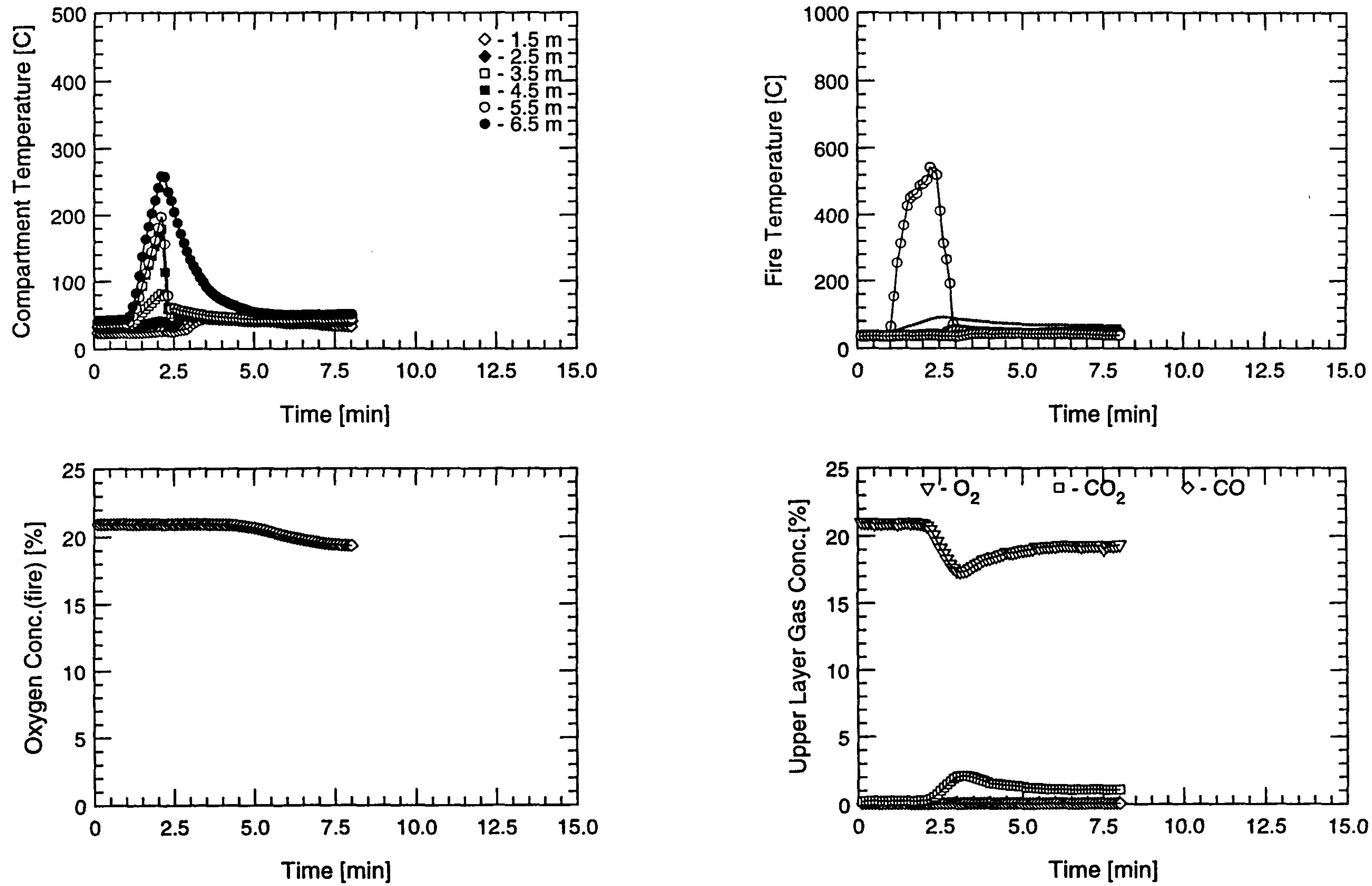


Fire Temperature [C]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Oxygen Conc.(fire) [%]
Time [min]

Test #84

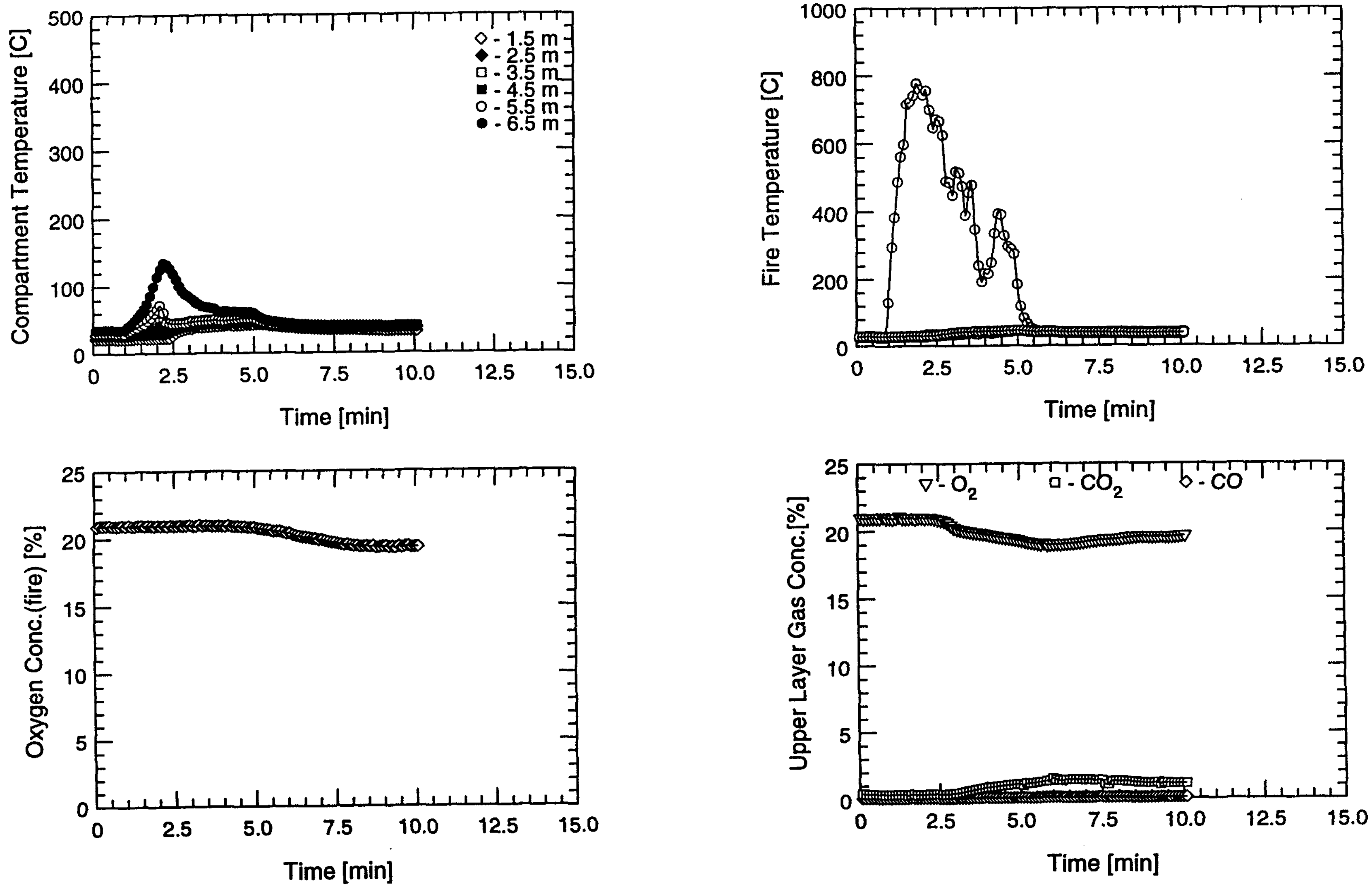

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #85

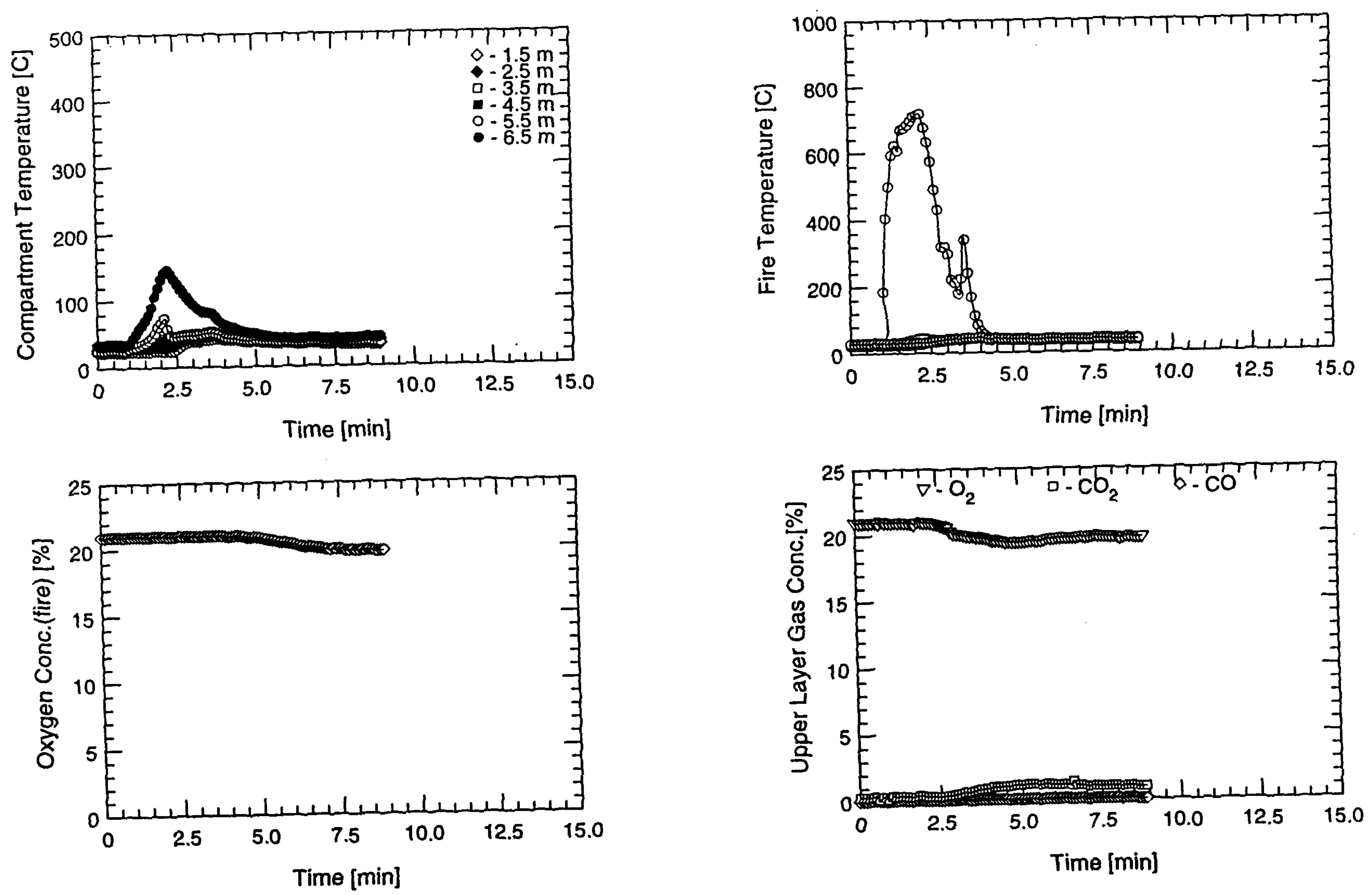


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #86

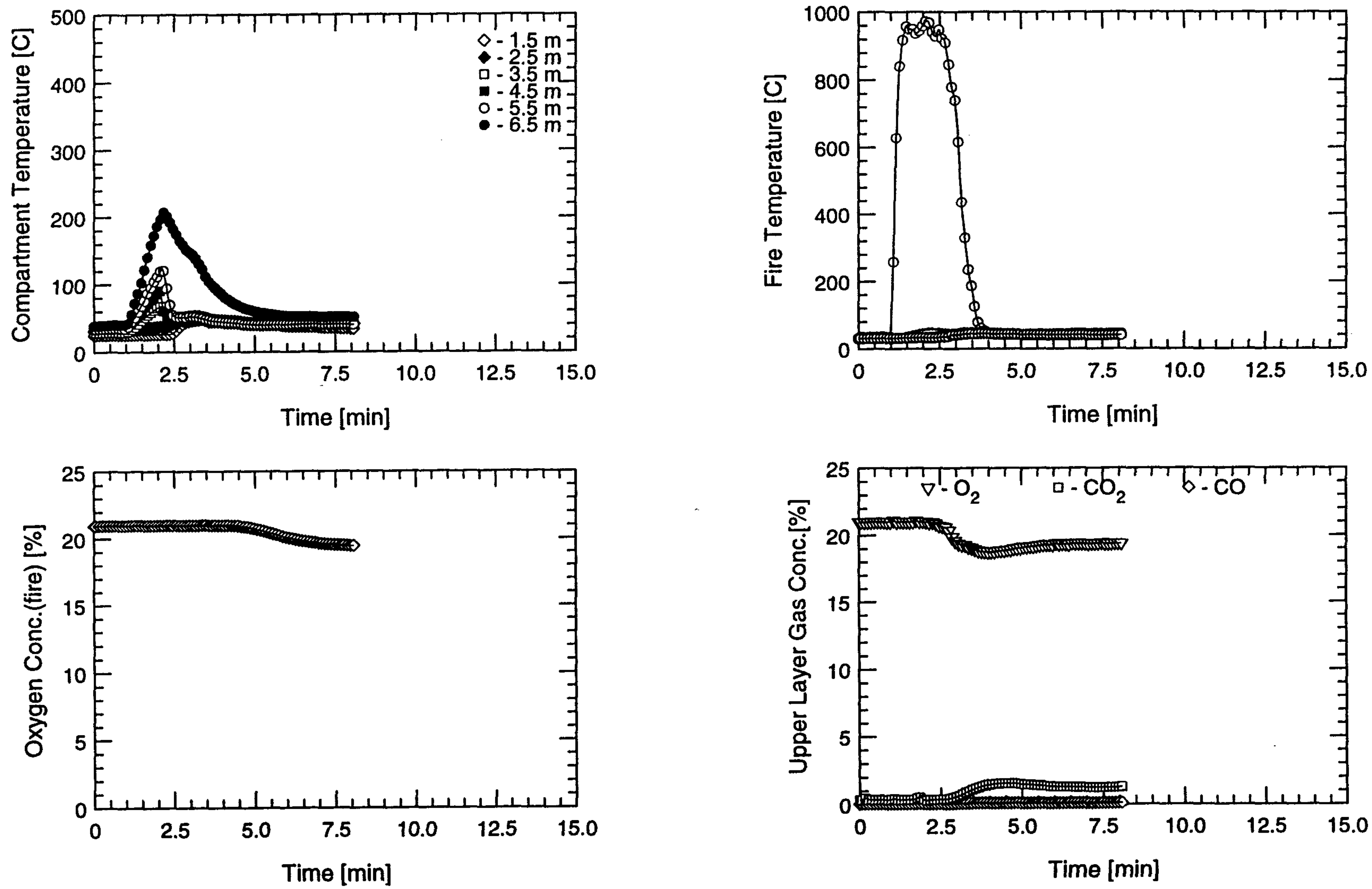

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #87

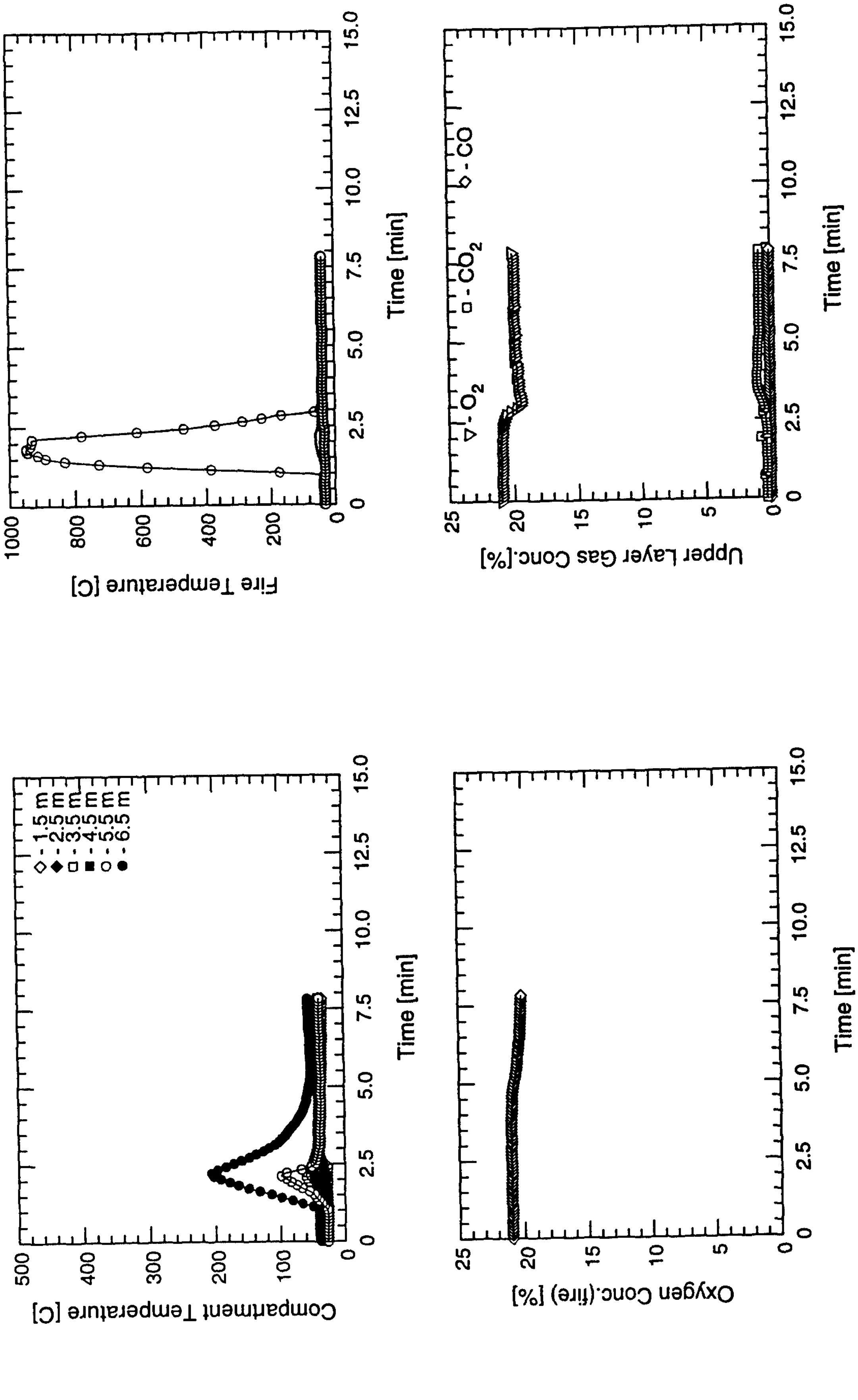


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

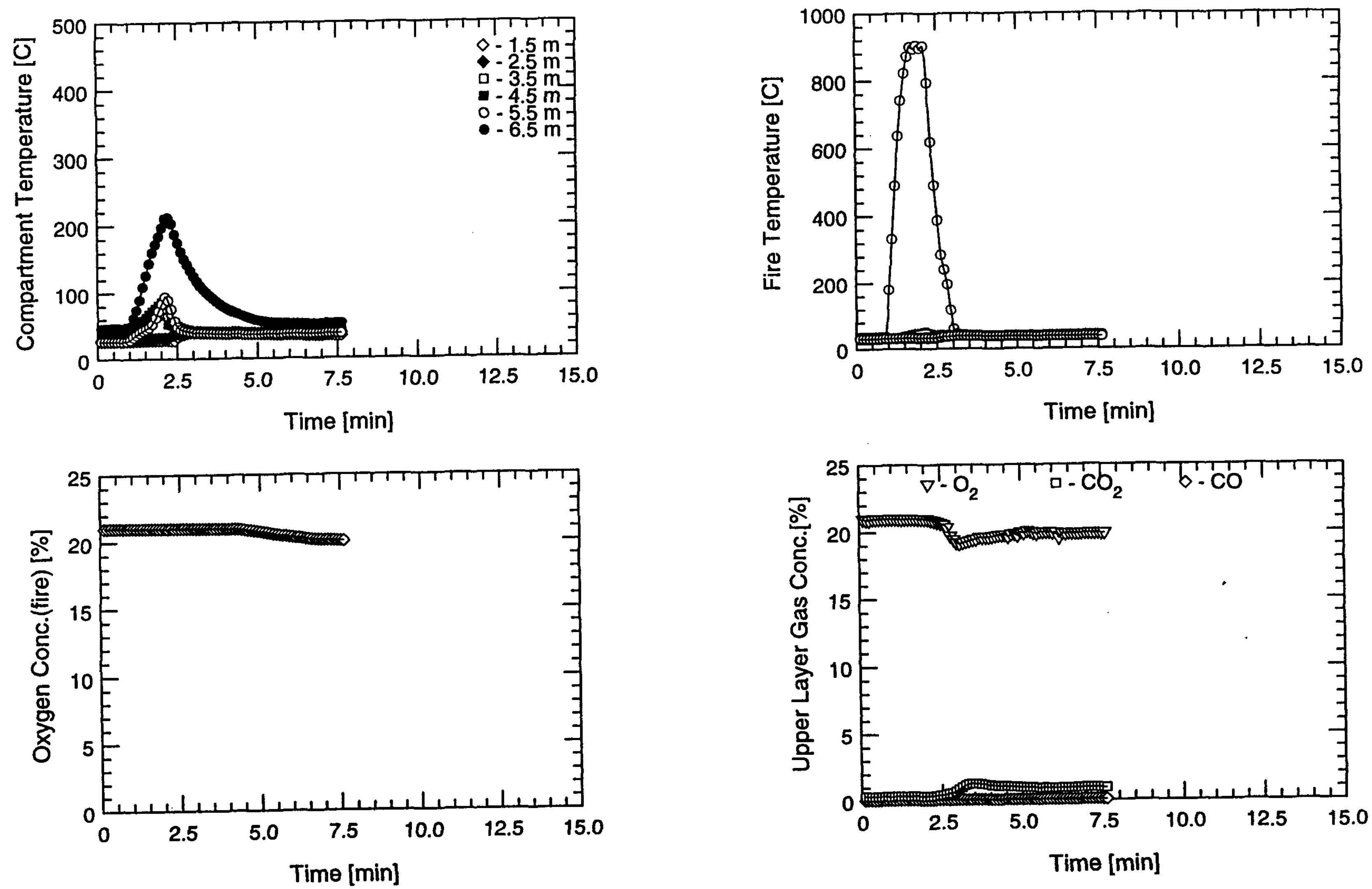
Test #88


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #89

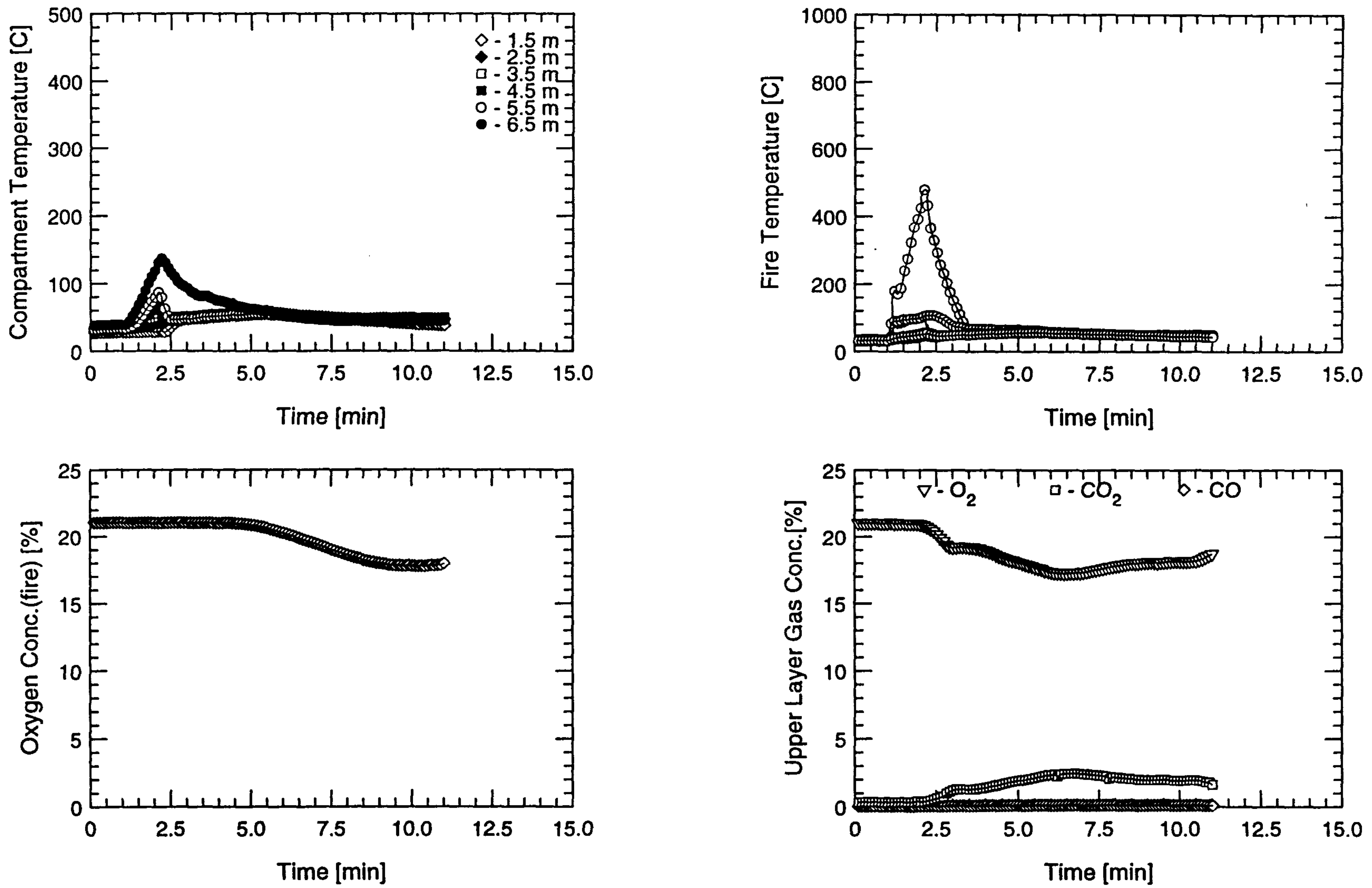

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #90



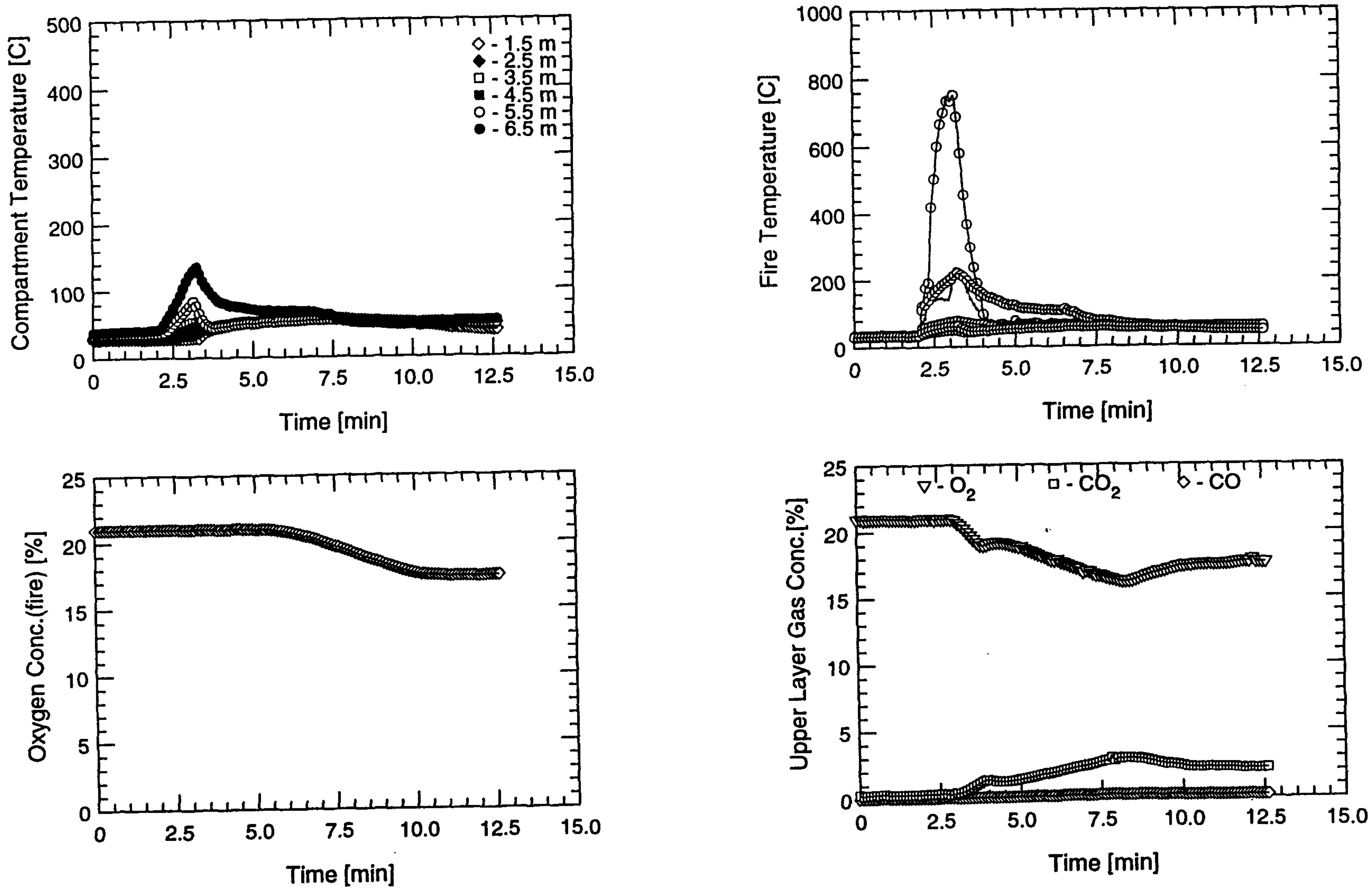
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #91



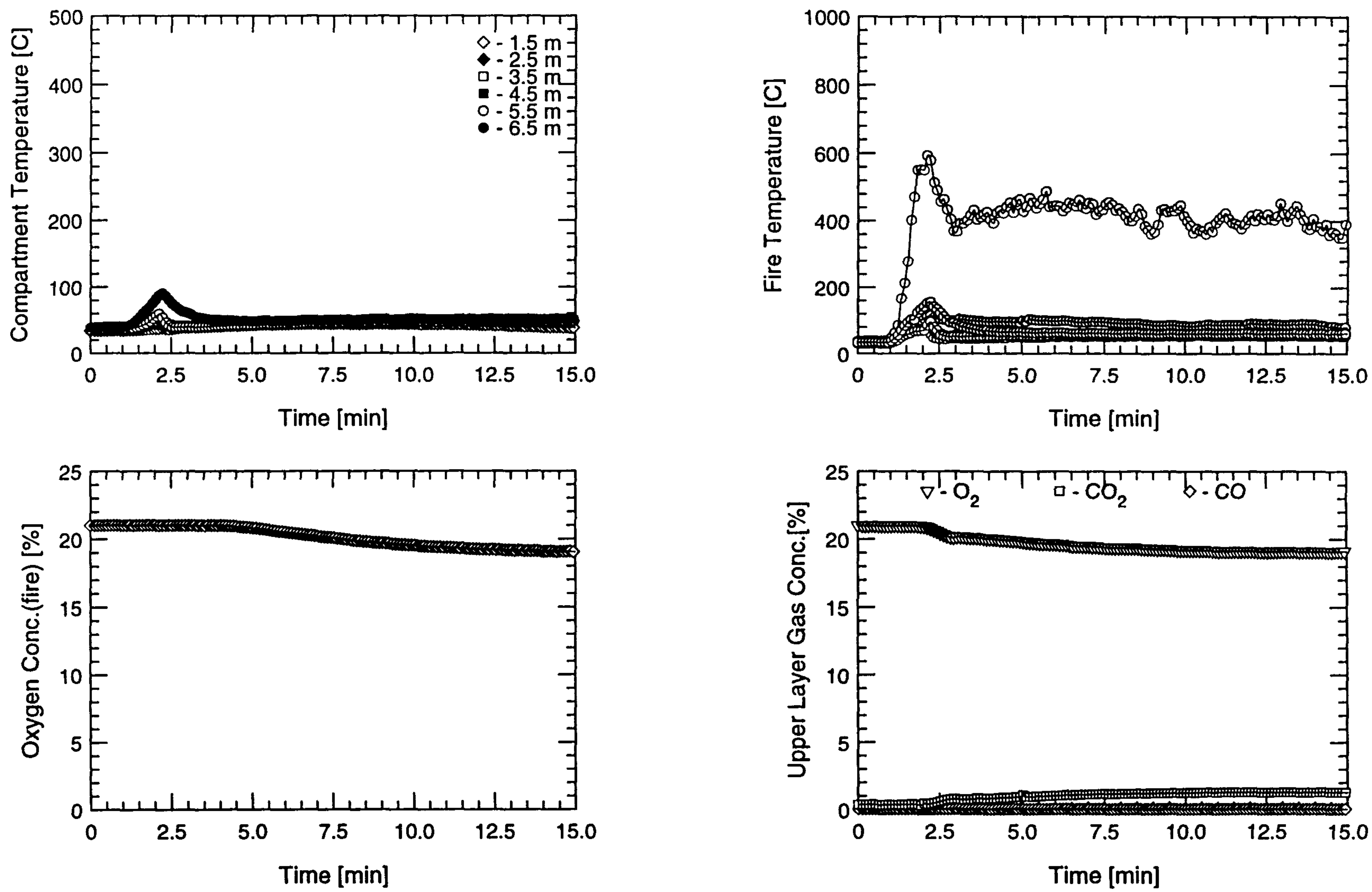
Compartment Temperature [C]
0
100
200
300
400
500
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
0
2.5
5.0
7.5
10.0
12.5
15.0
Fire Temperature [C]
0
200
400
600
800
1000
Time [min]
Oxygen Conc.(fire) [%]
0
5
10
15
20
25
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #92

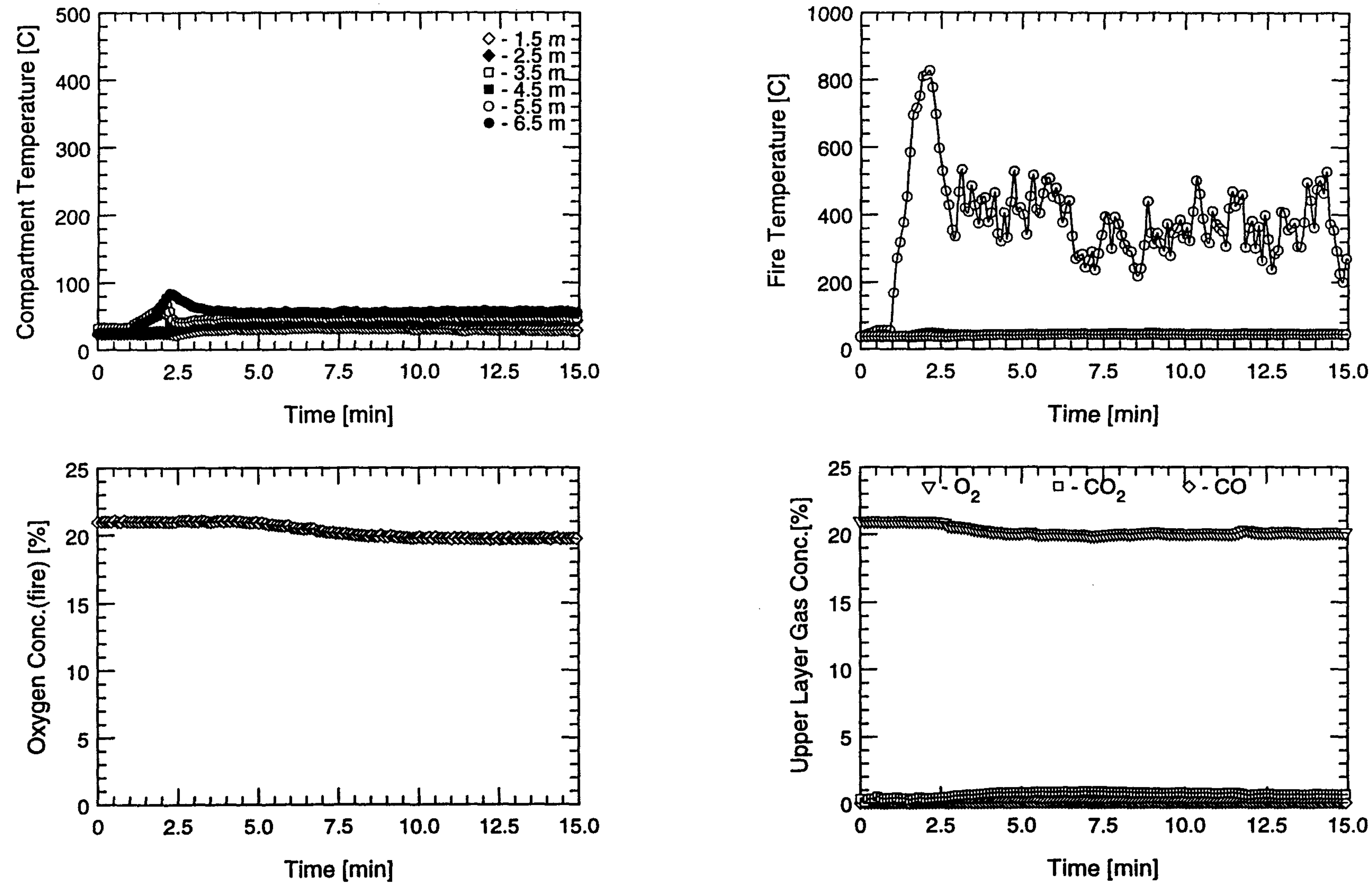


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #93

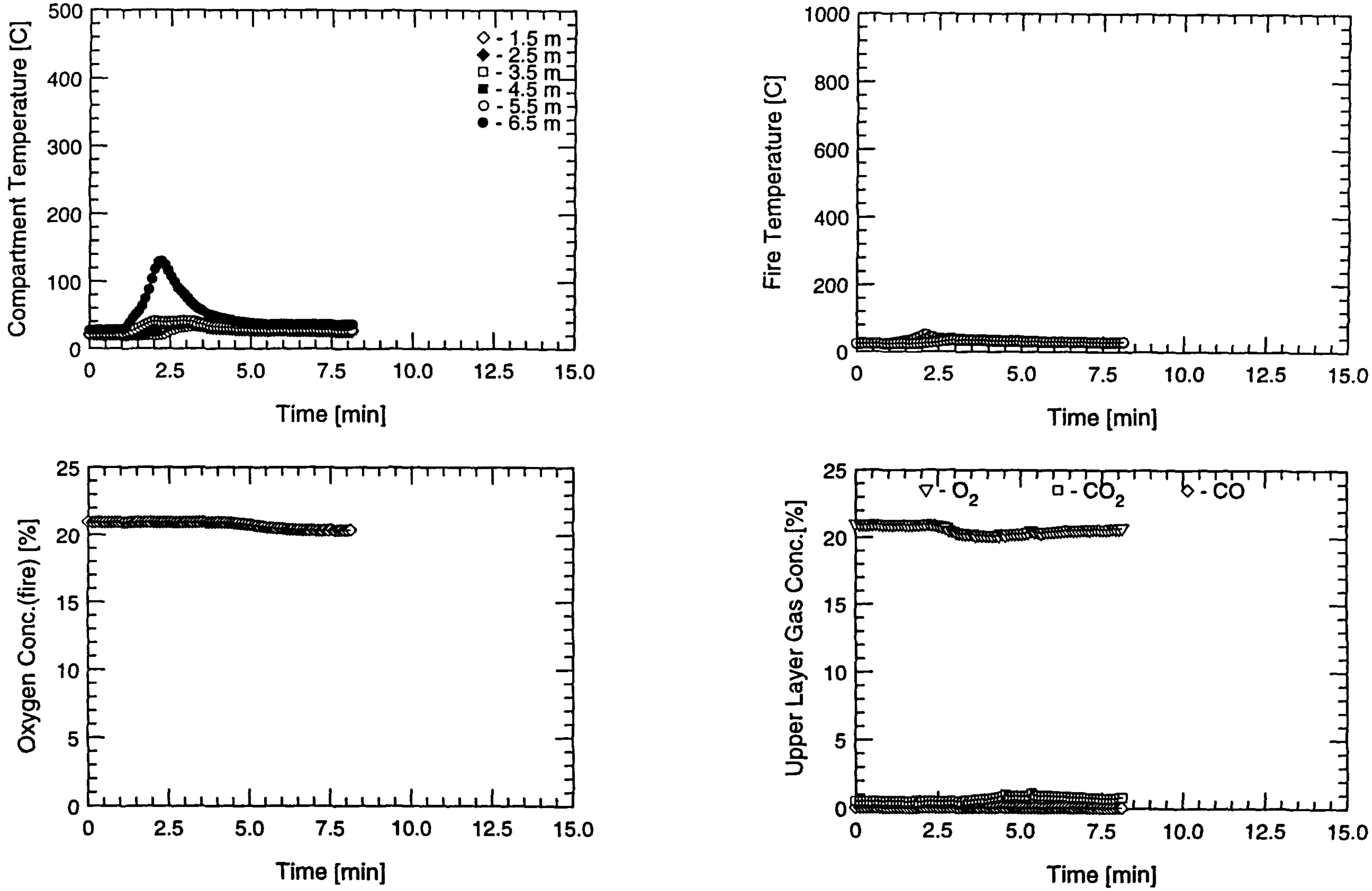

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #94

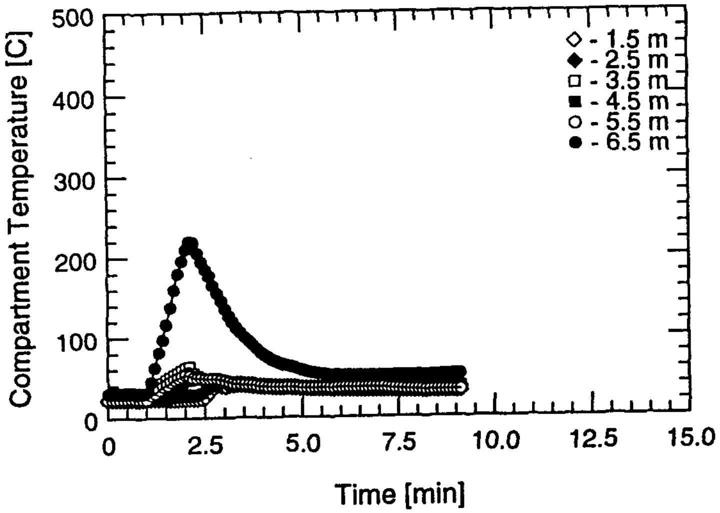


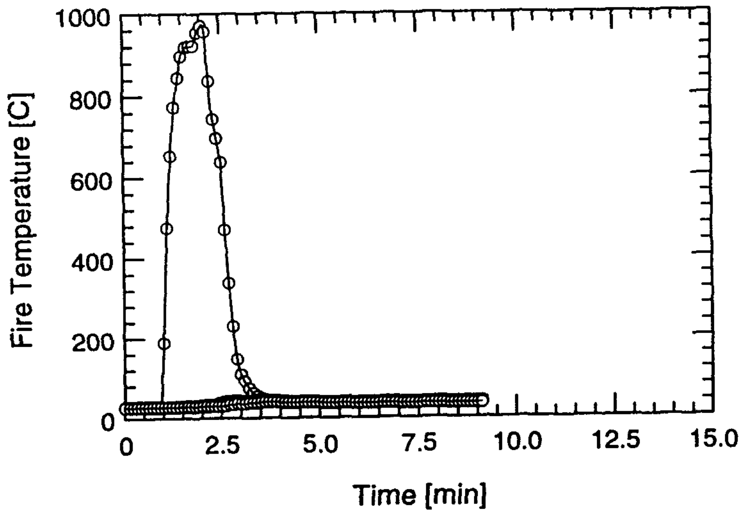
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

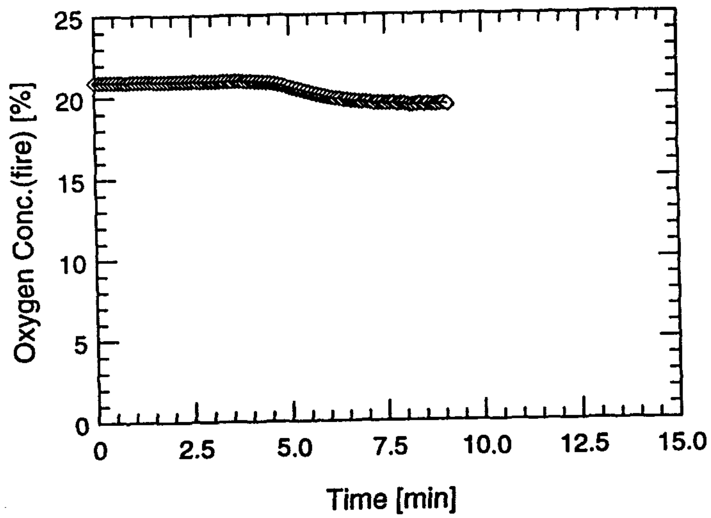
Test #95

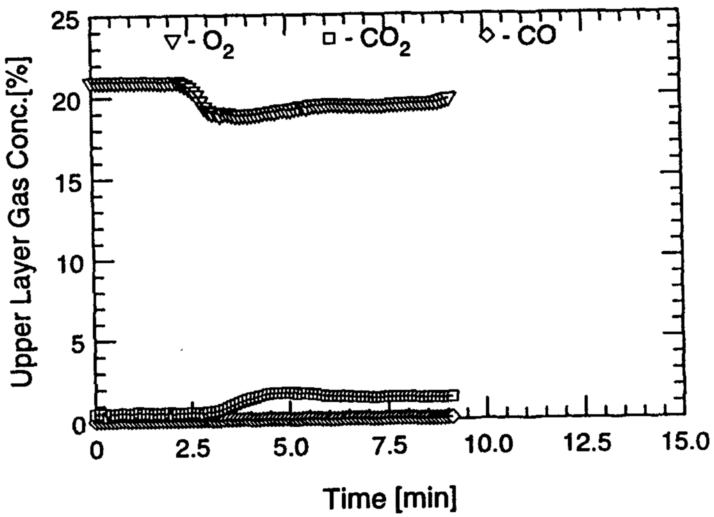

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #96

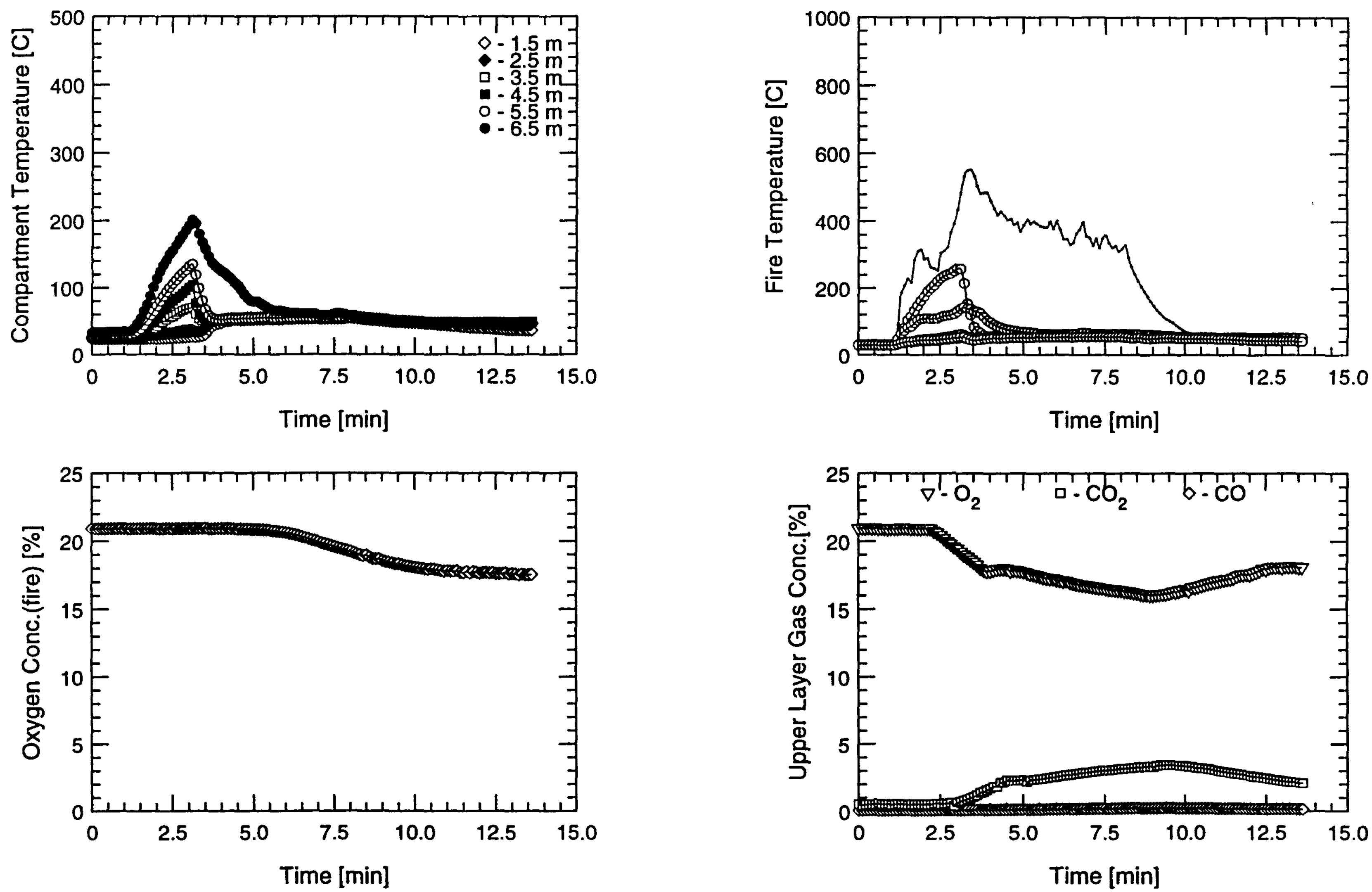

◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Compartment Temperature [C]
Time [min]


Fire Temperature [C]
Time [min]

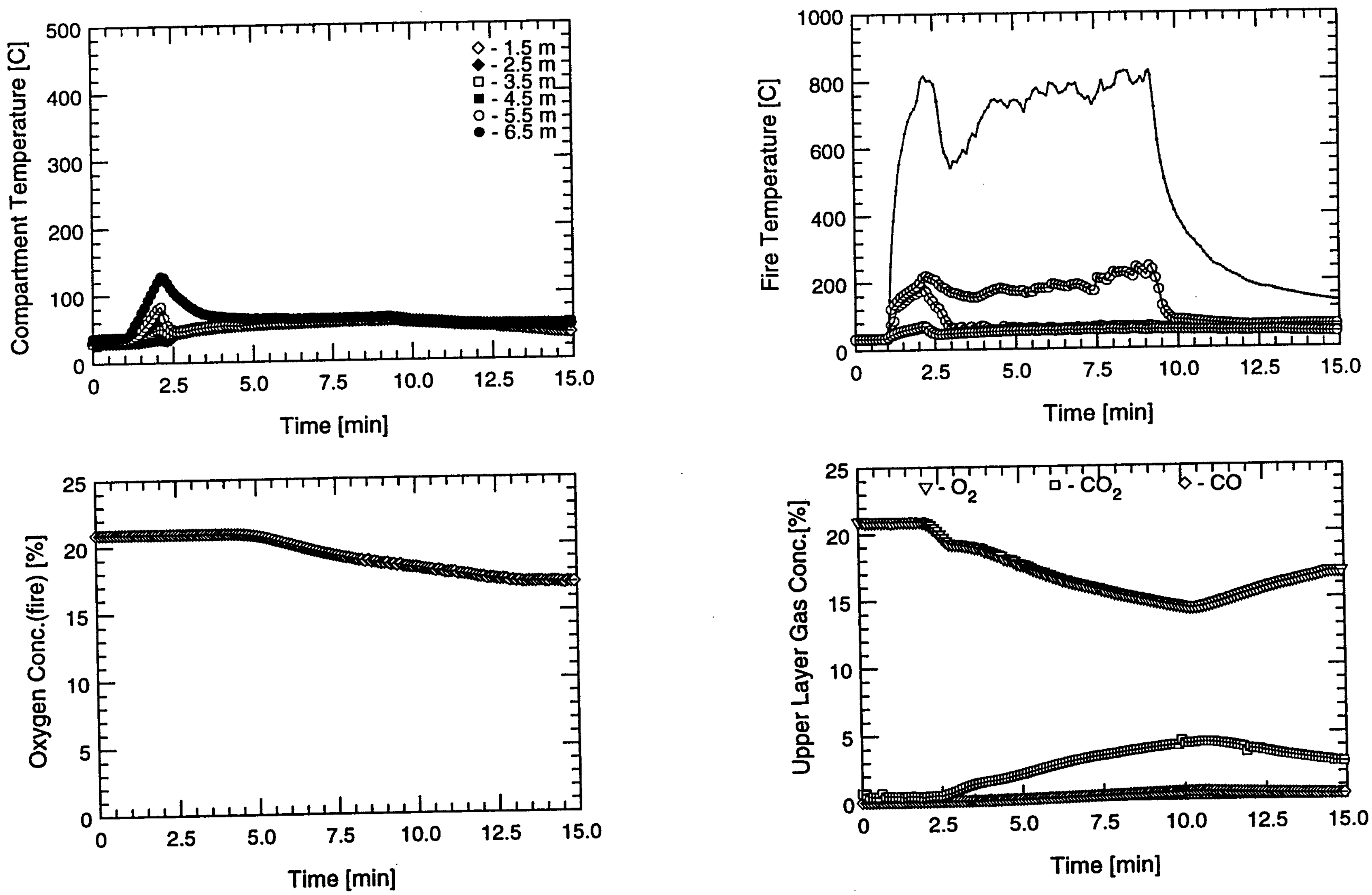

Oxygen Conc.(fire) [%]
Time [min]


▽ - O_2
□ - CO_2
◇ - CO
Upper Layer Gas Conc.[%]
Time [min]

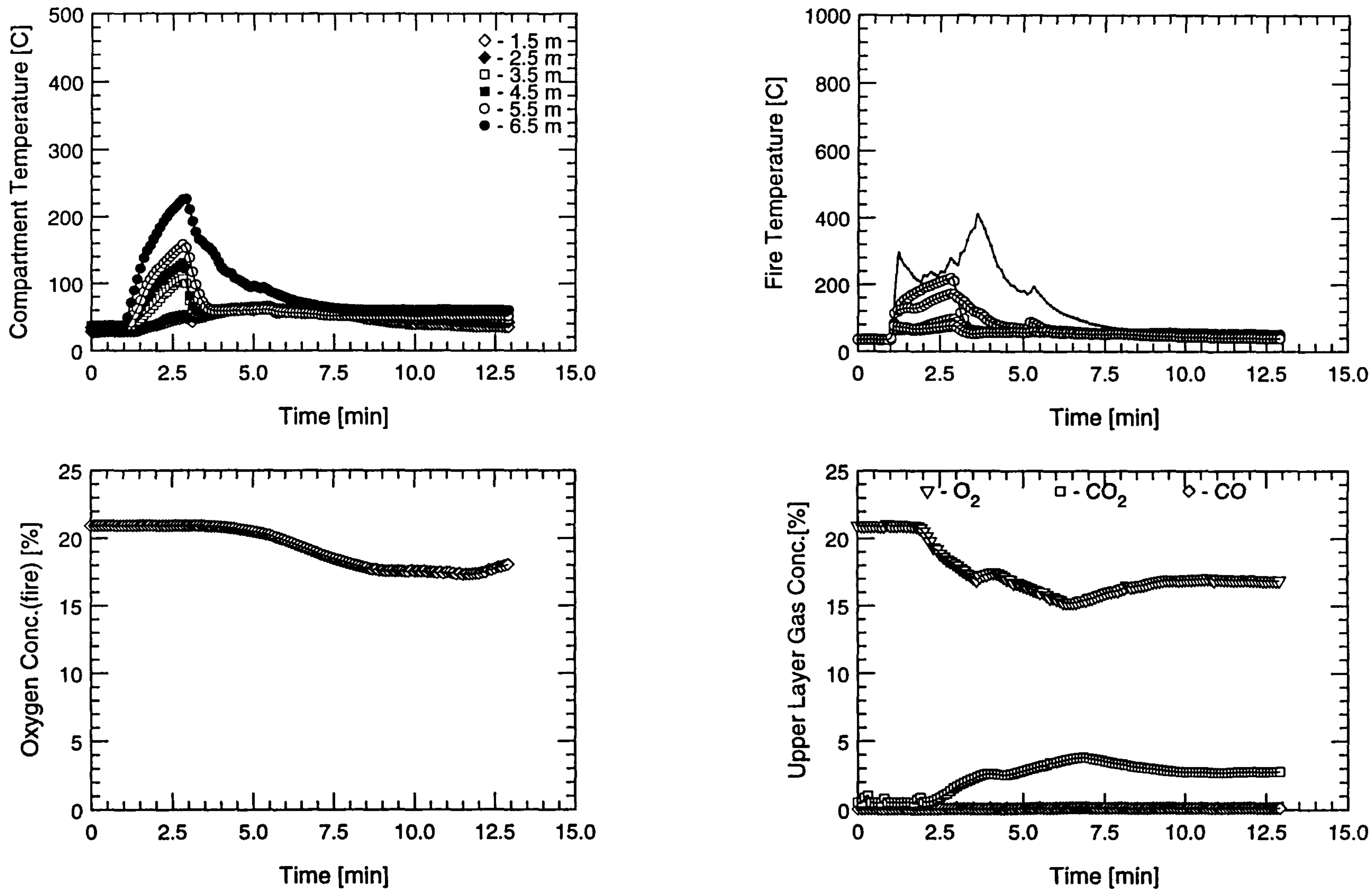
Test #97


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
0
2.5
5.0
7.5
10.0
12.5
15.0
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
∇ - O_2
□ - CO_2
◇ - CO
Time [min]

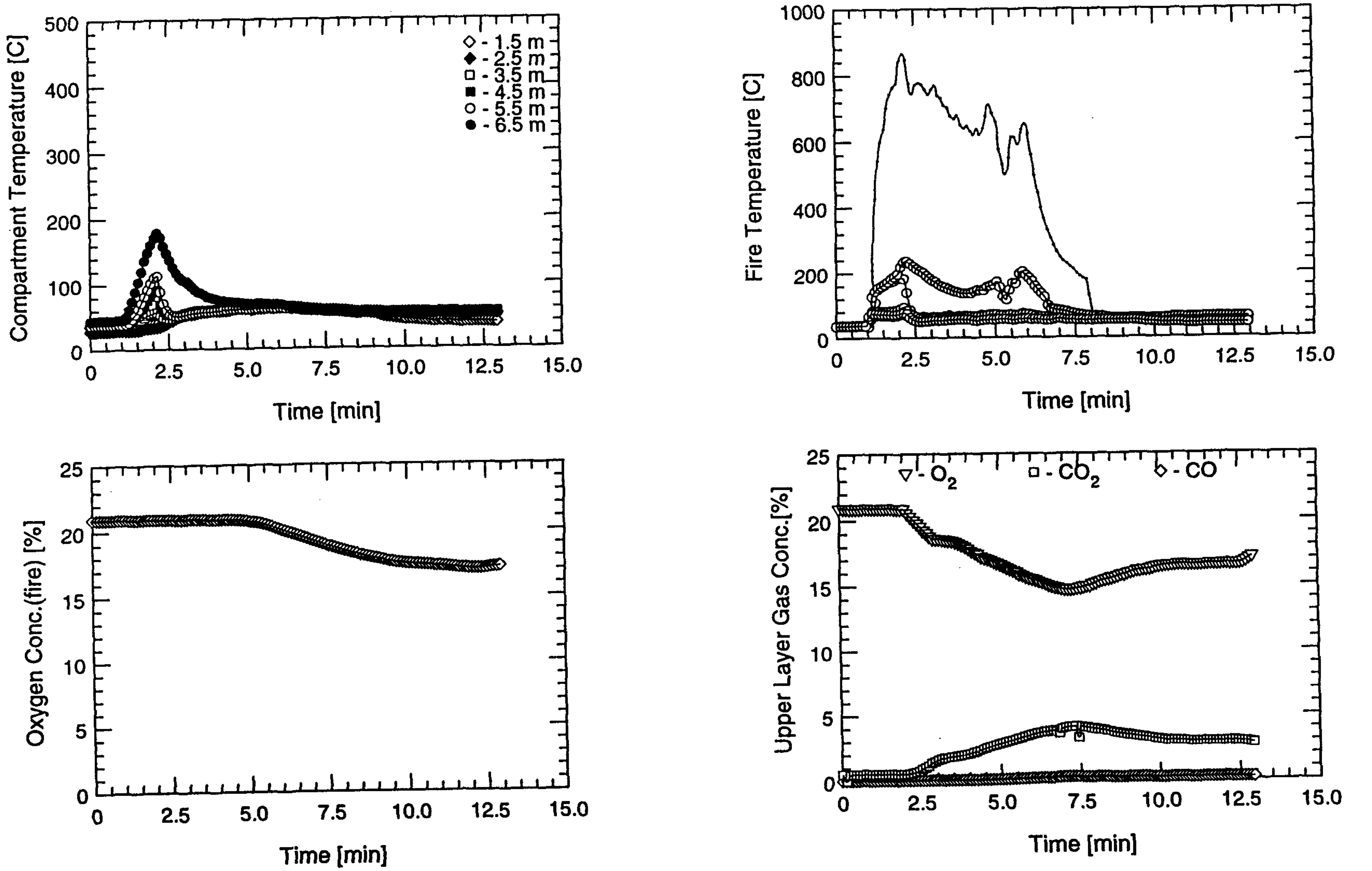
Test #98


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

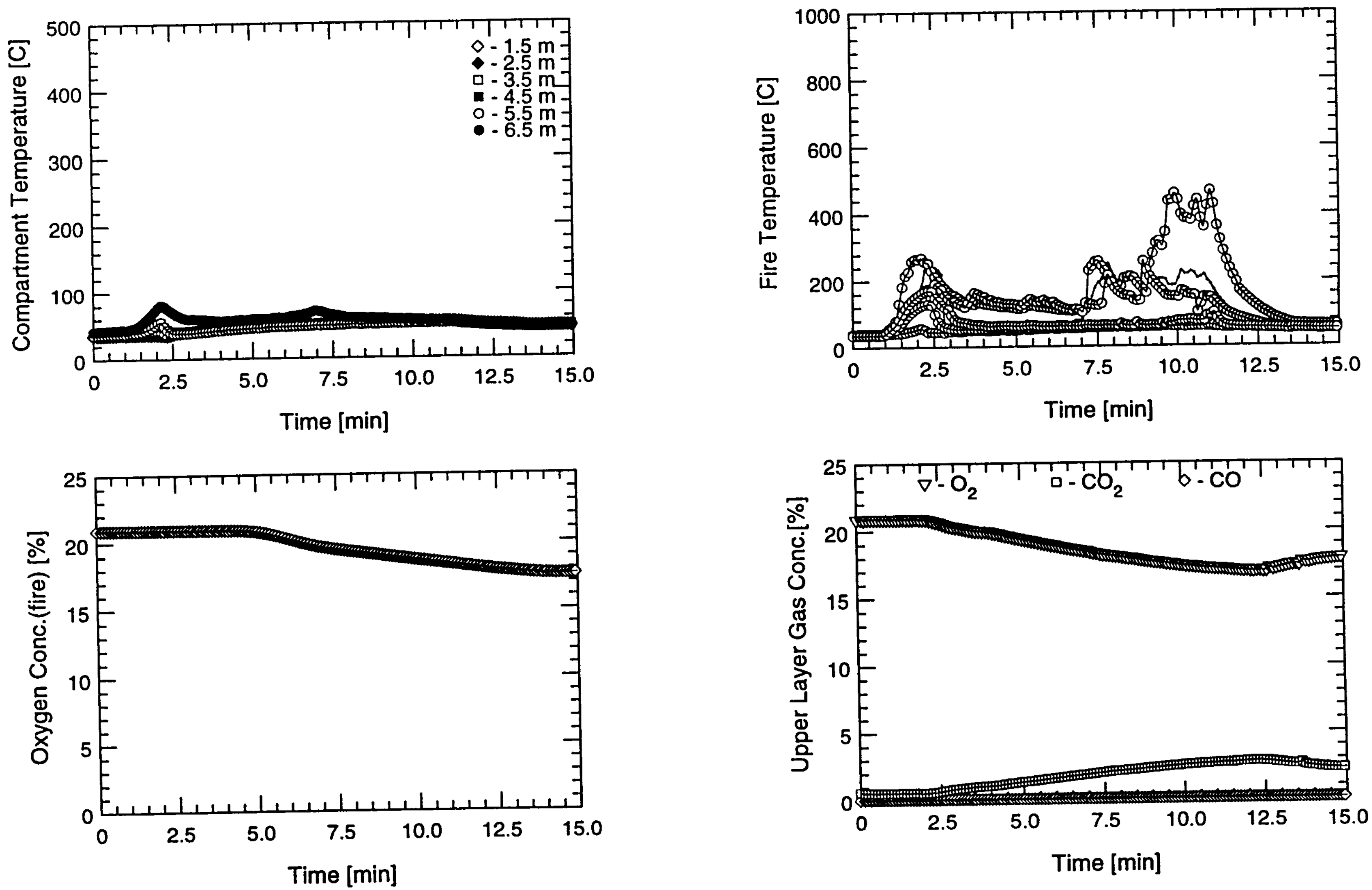
Test #99


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #100

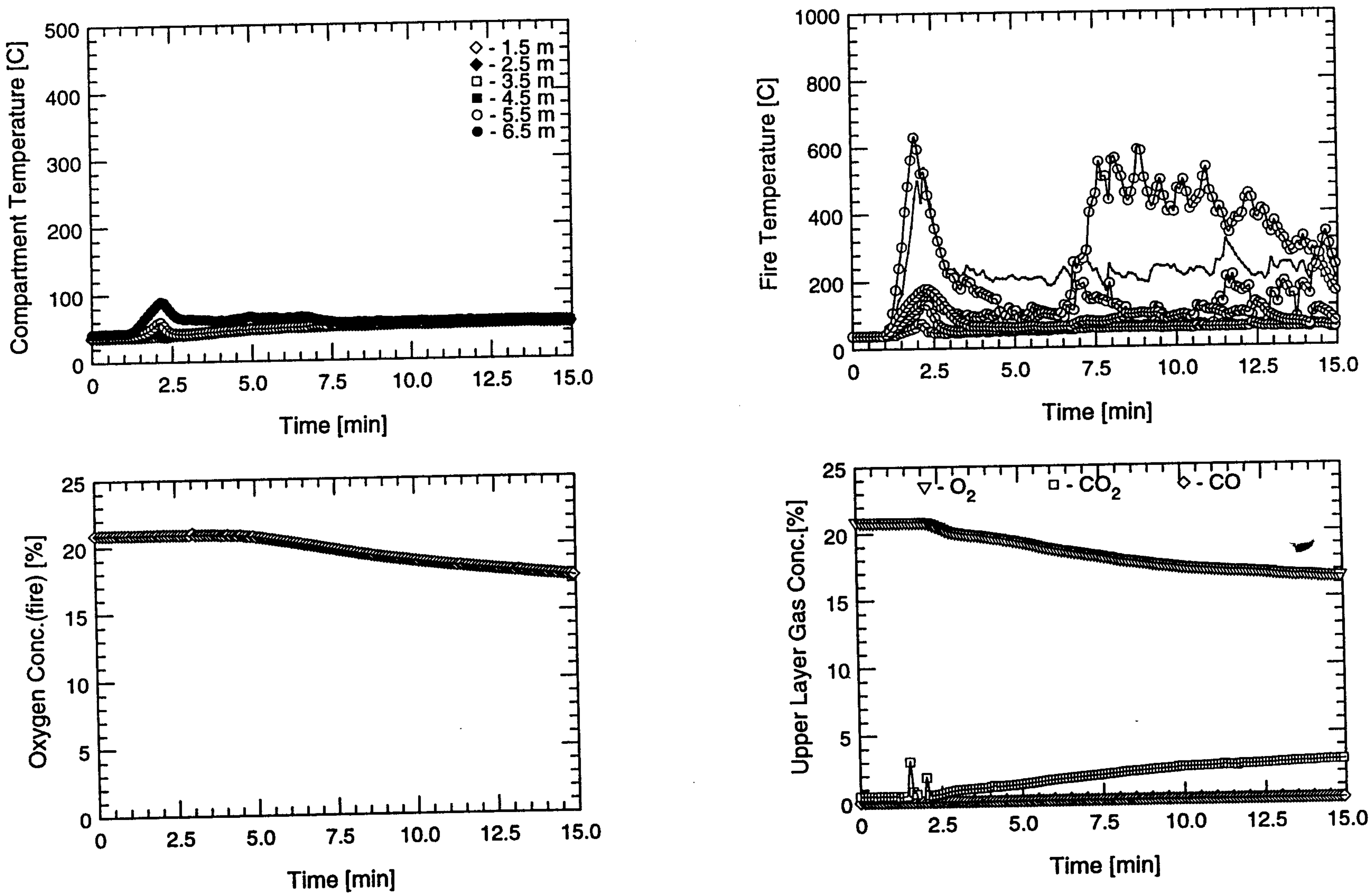

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #101

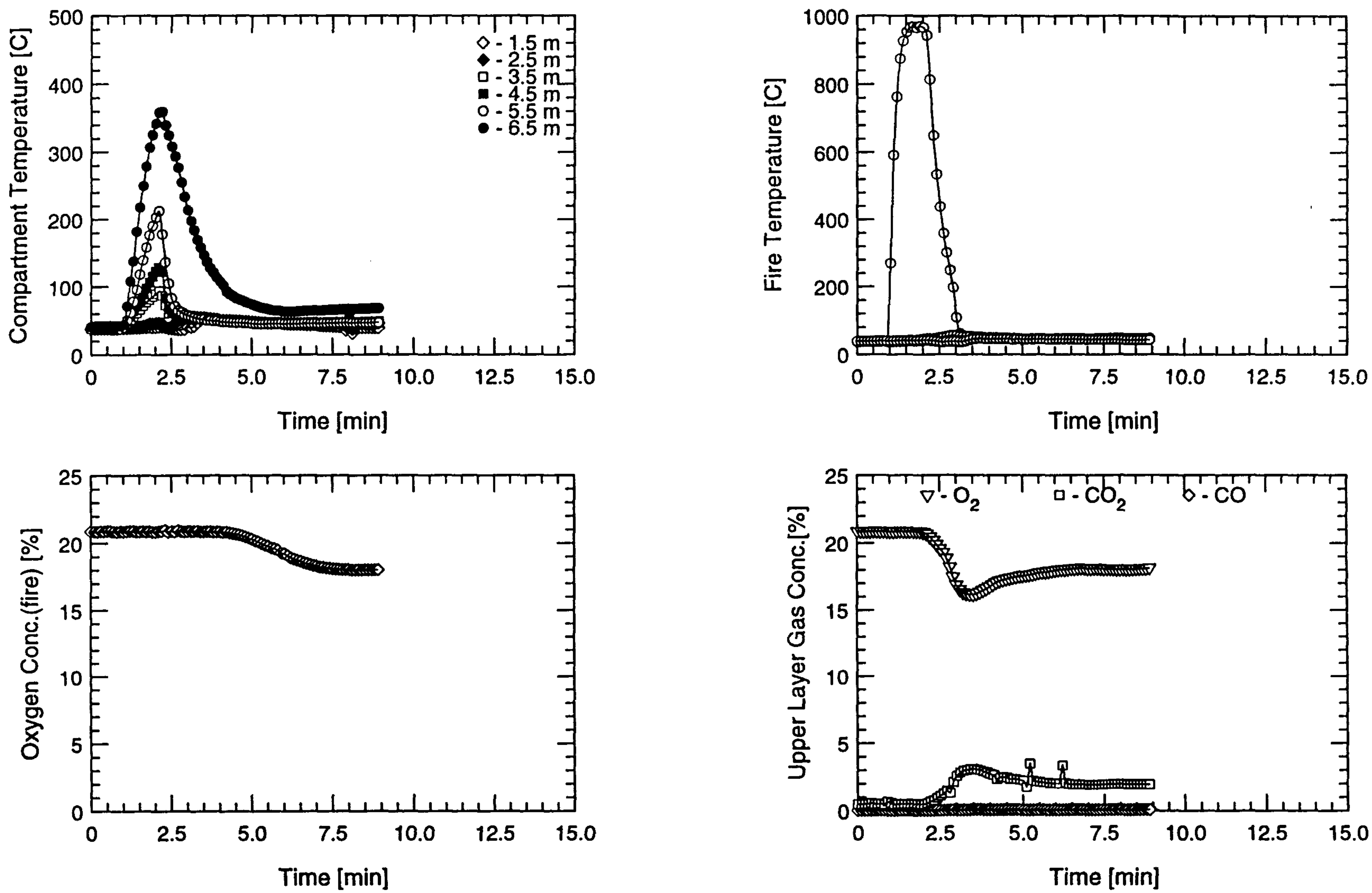


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
0
2.5
5.0
7.5
10.0
12.5
15.0
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #102

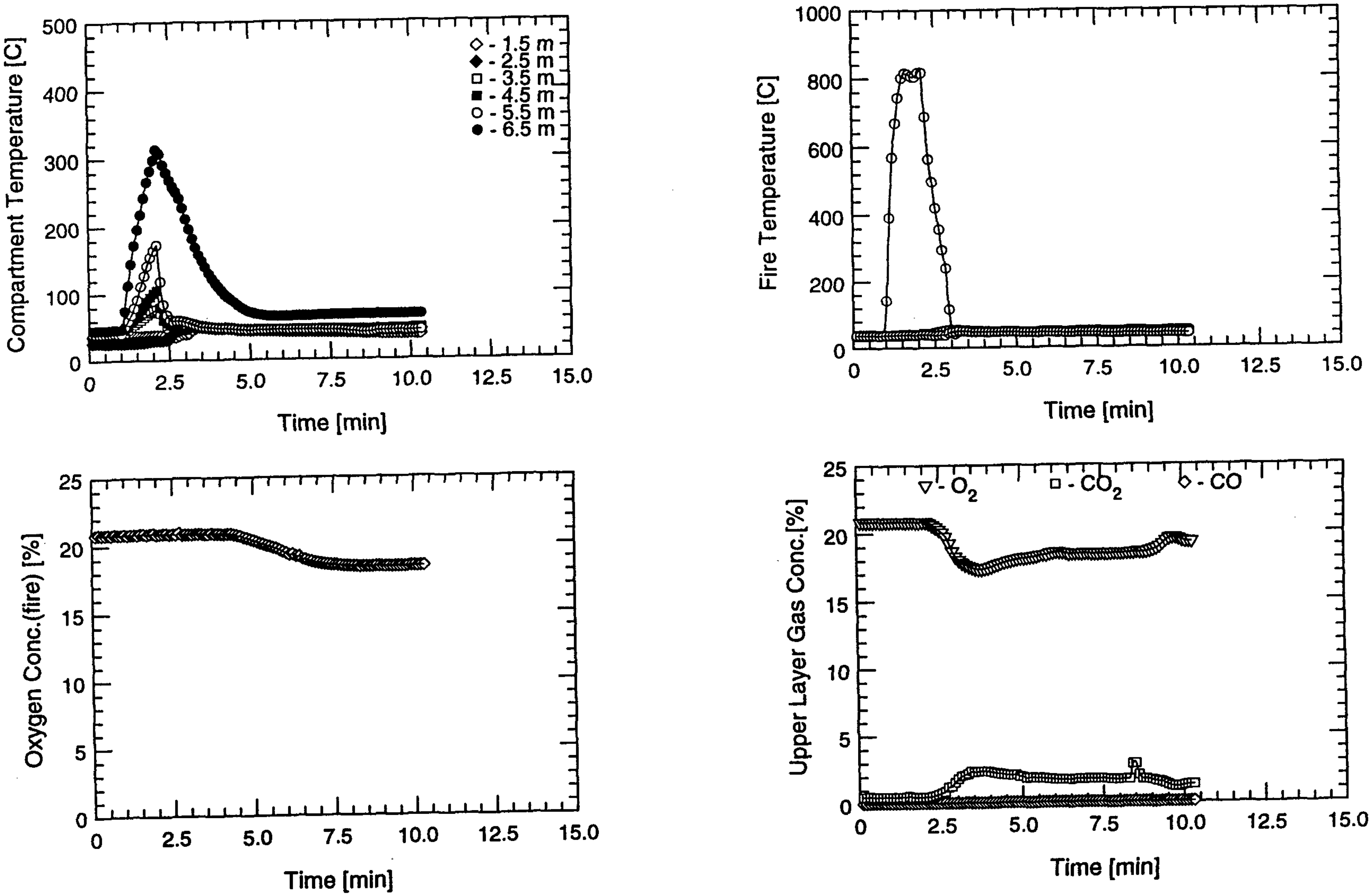

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #103

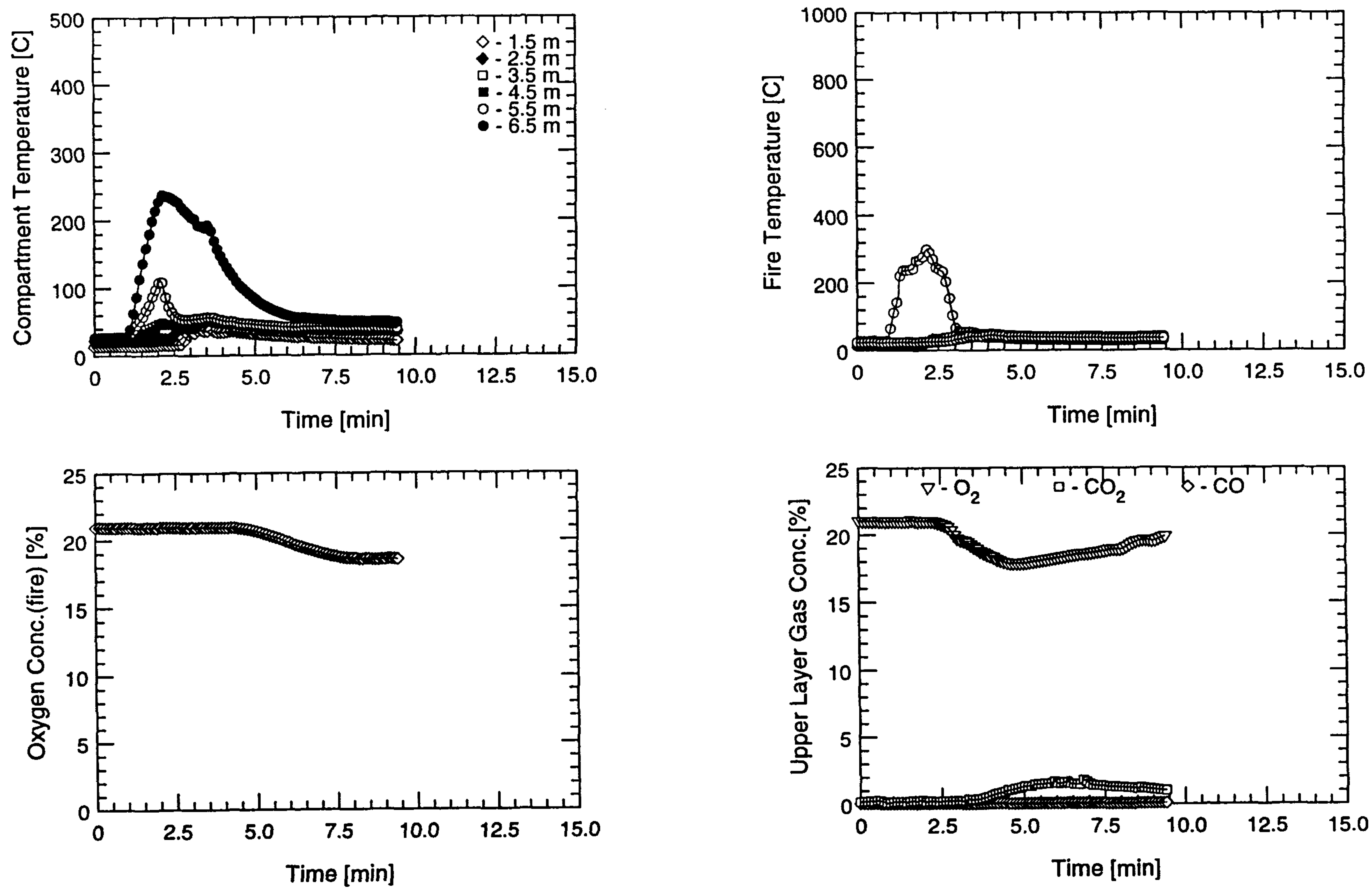


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O2
□ - CO2
◇ - CO

Test #104

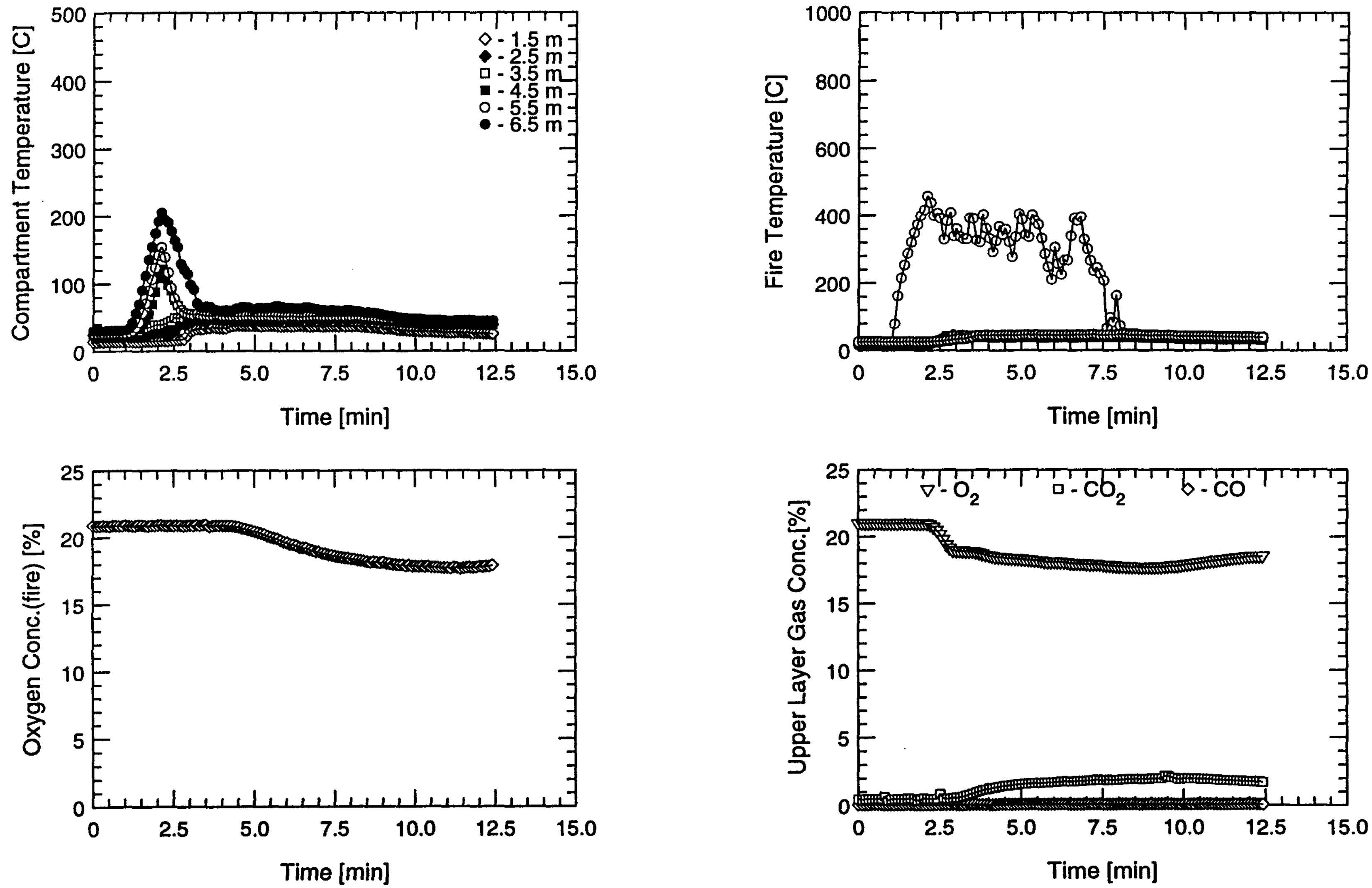

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O2
□ - CO2
◇ - CO

Test #105

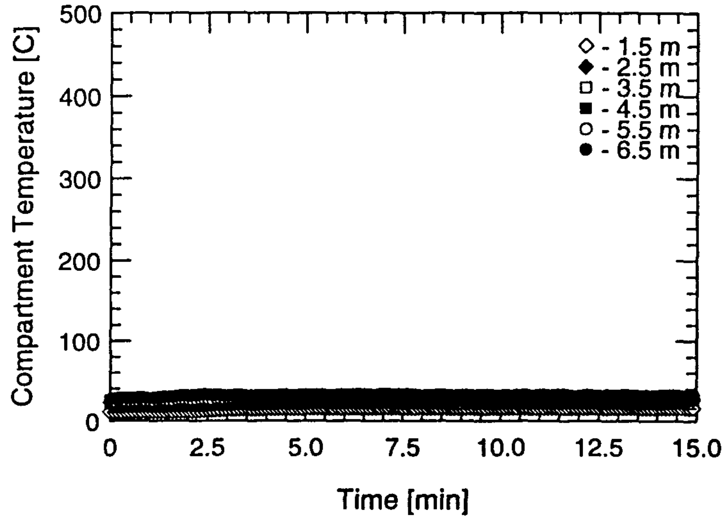


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

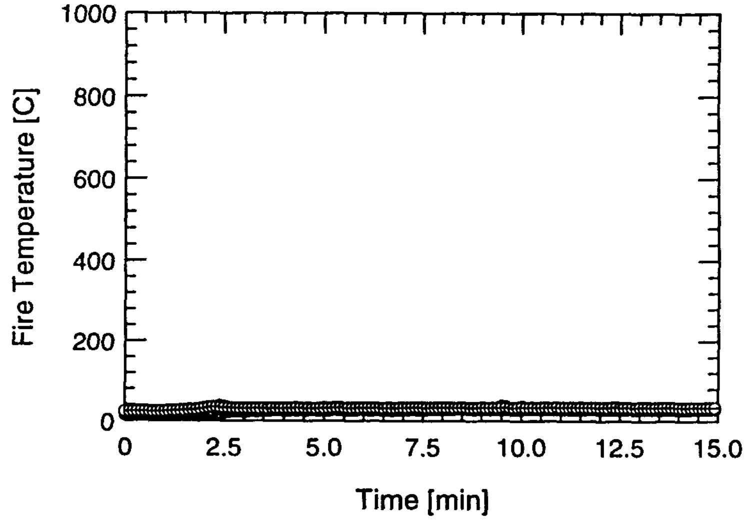
Test #106


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

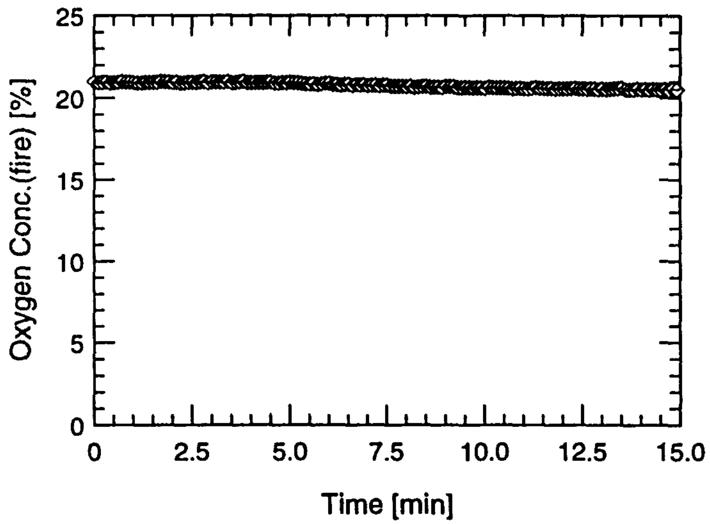
Test #107



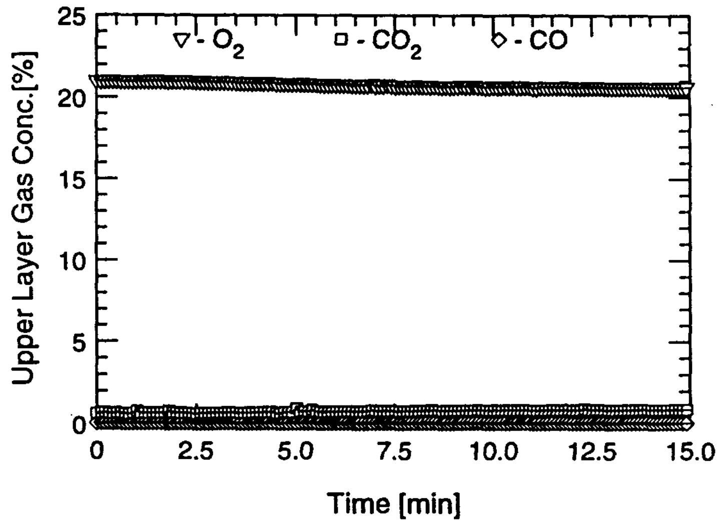
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]



Fire Temperature [C]
Time [min]

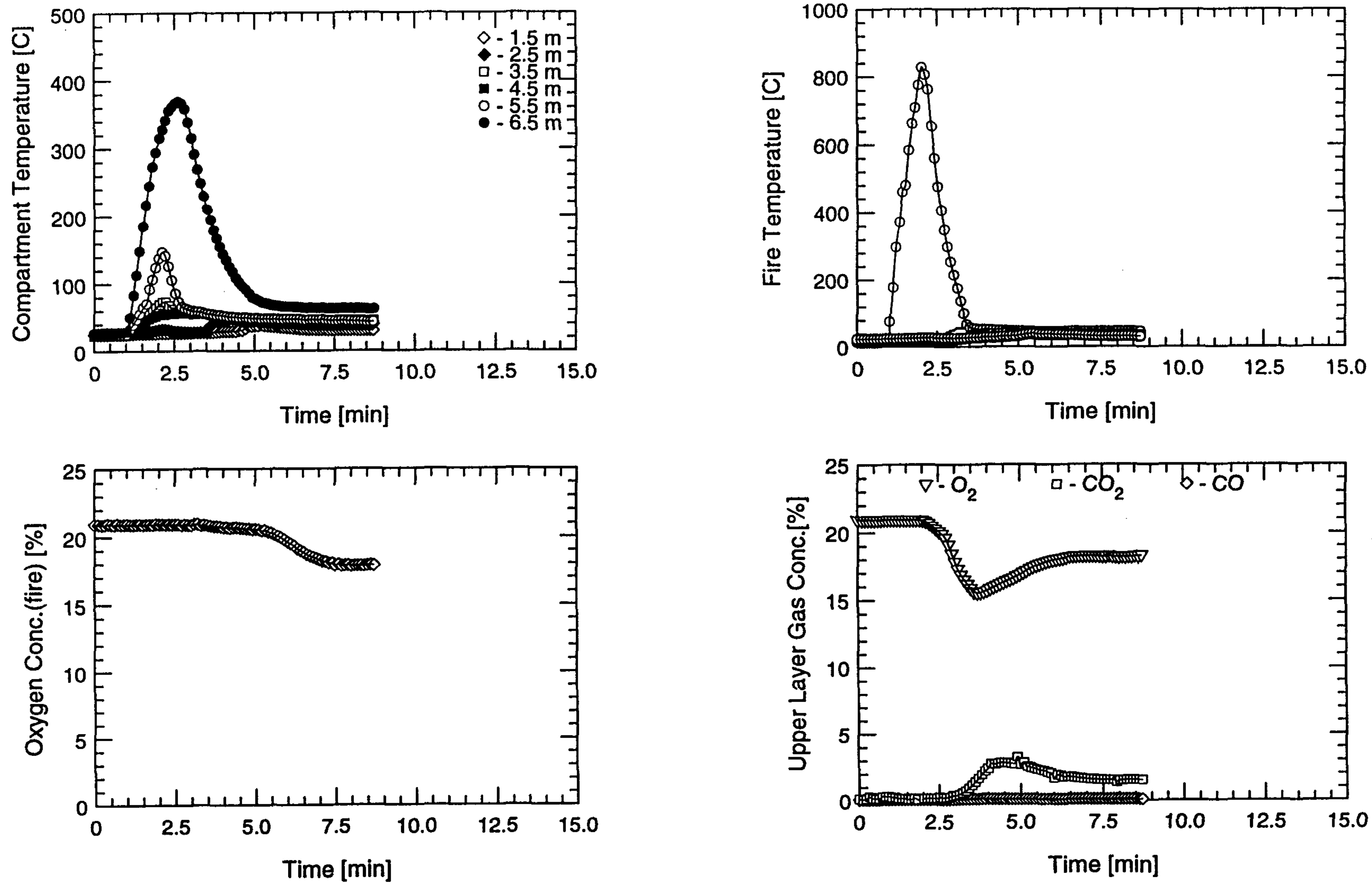


Oxygen Conc.(fire) [%]
Time [min]



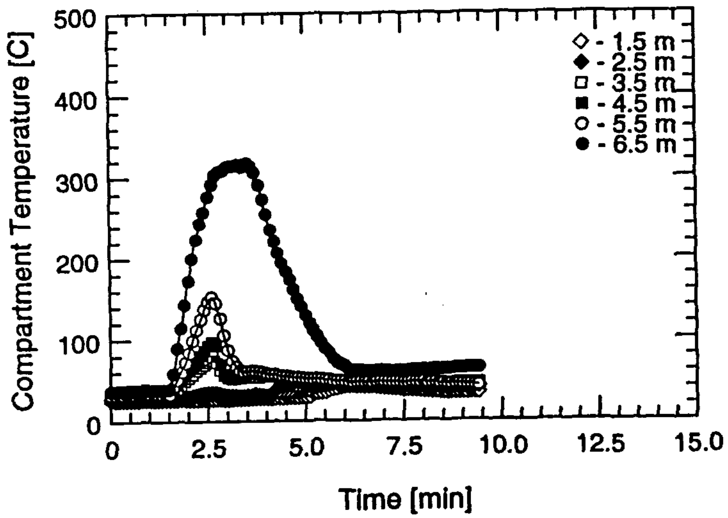
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #108

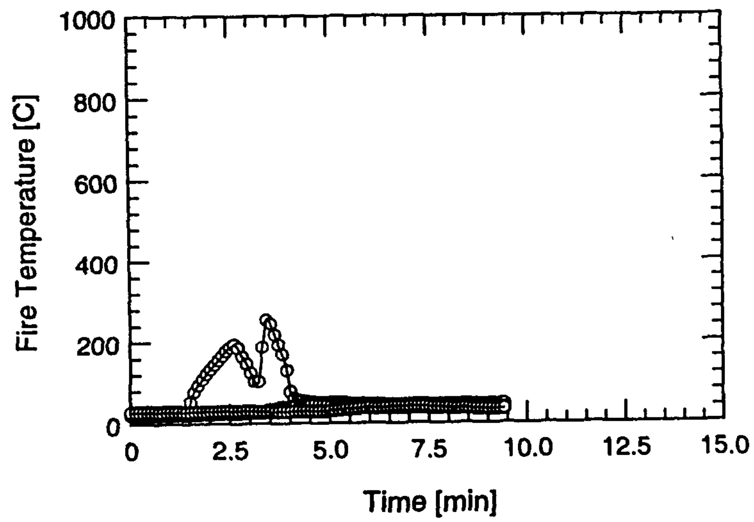


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

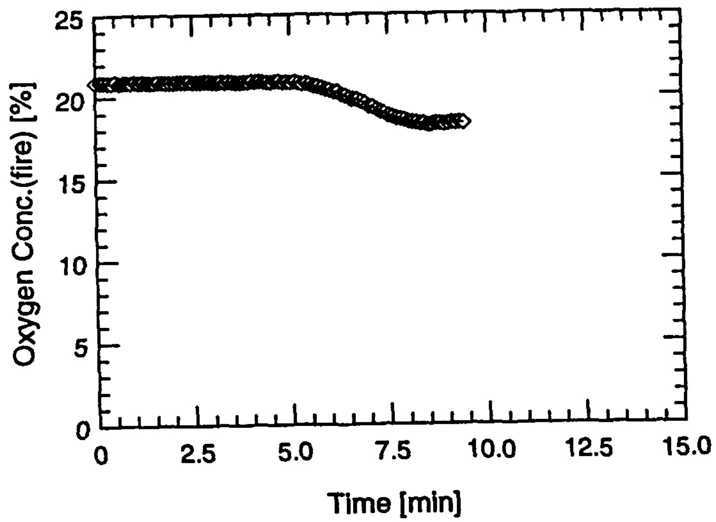
Test #109



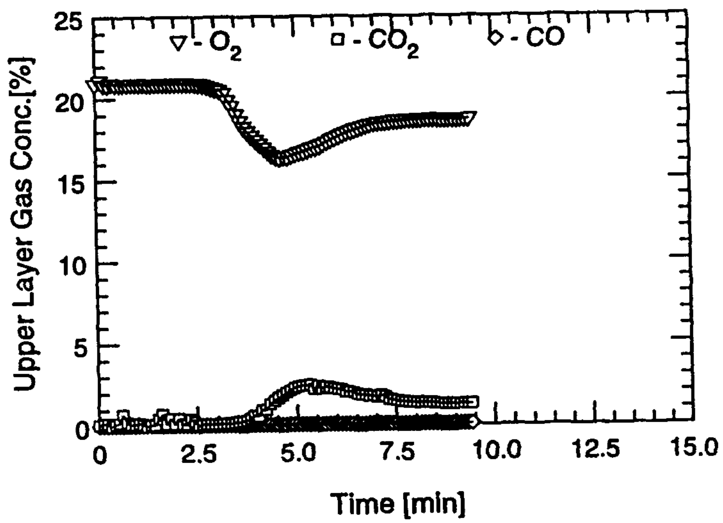
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m



Fire Temperature [C]
Time [min]

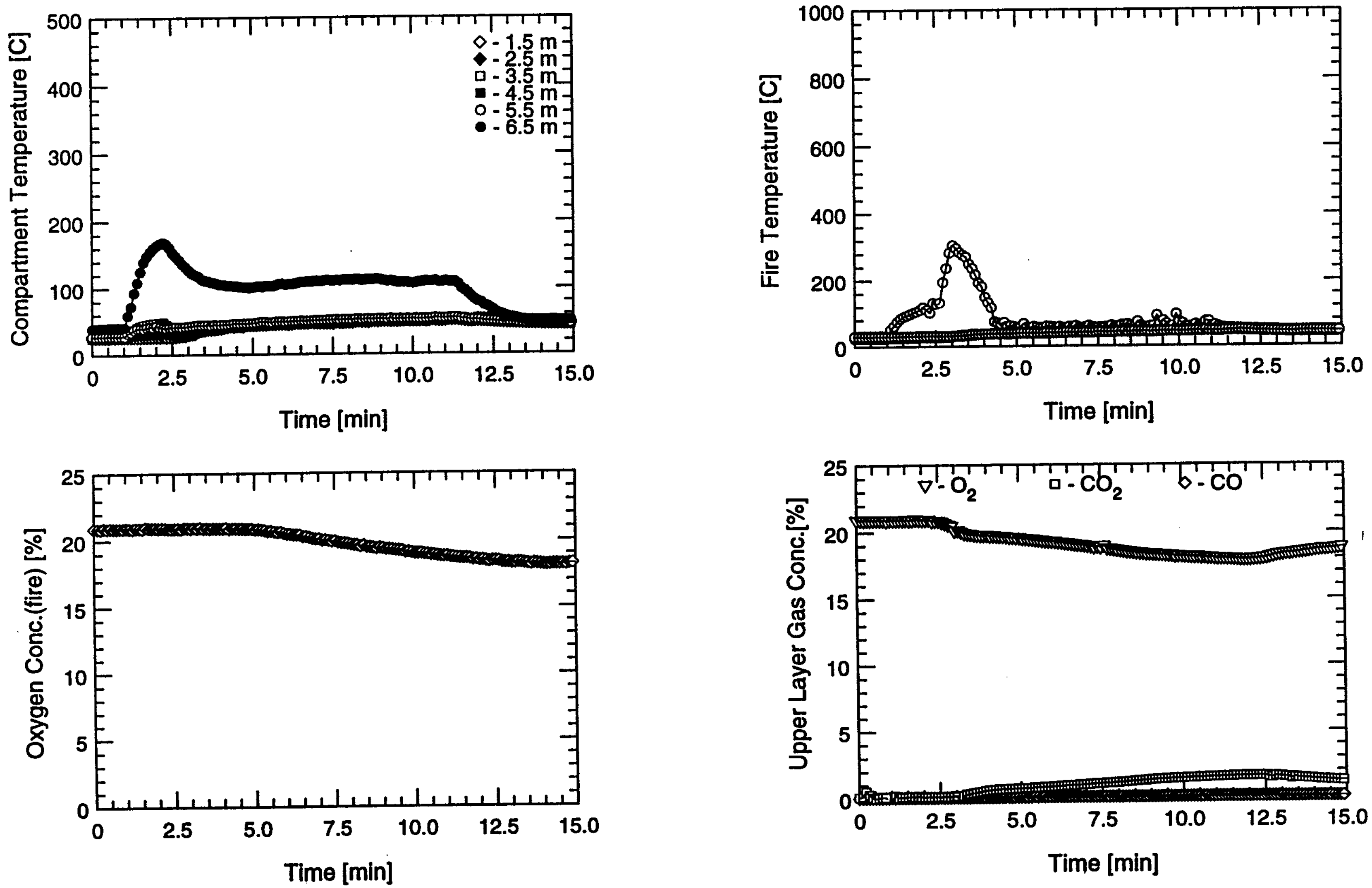


Oxygen Conc.(fire) [%]
Time [min]



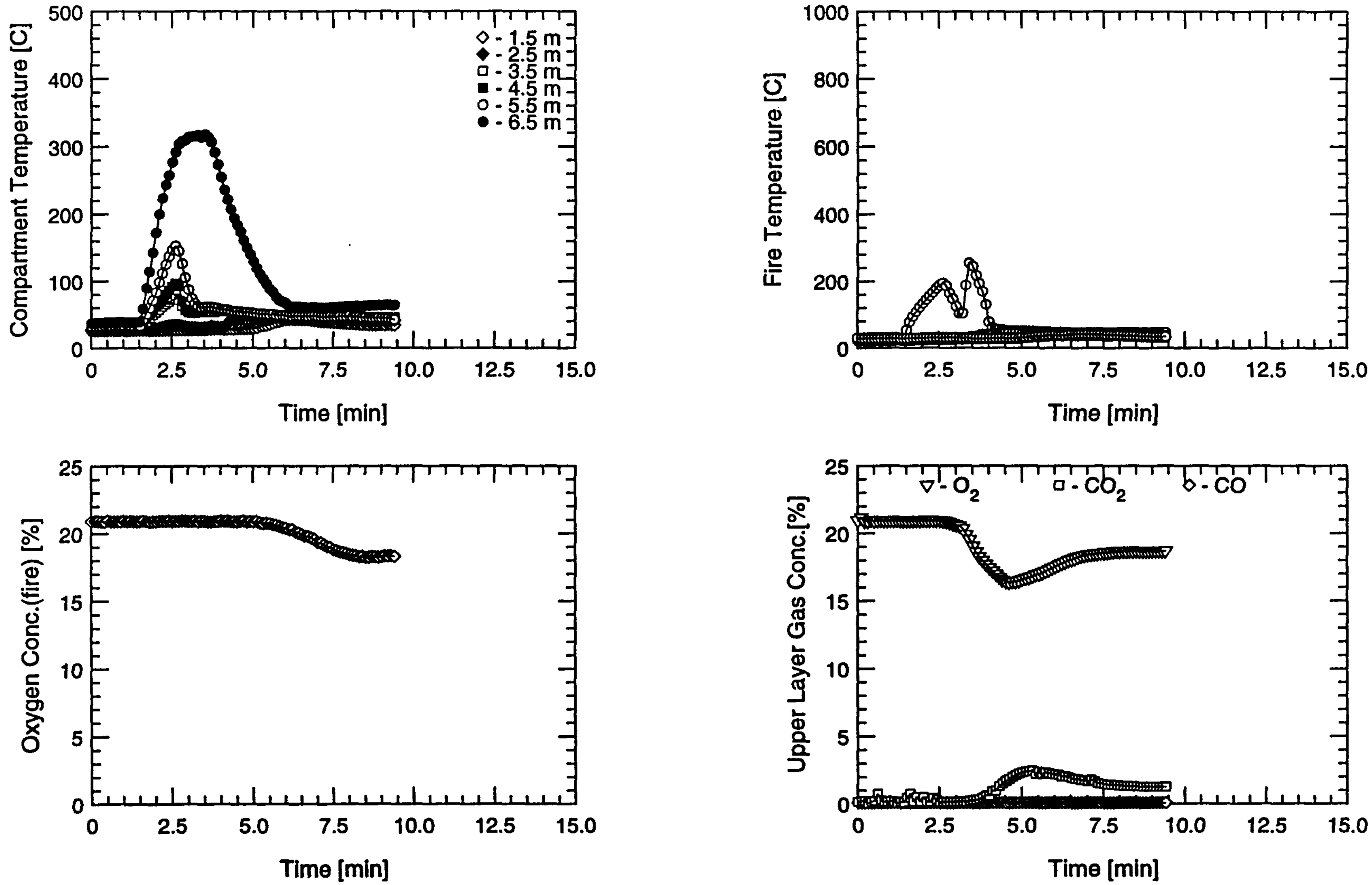
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #110



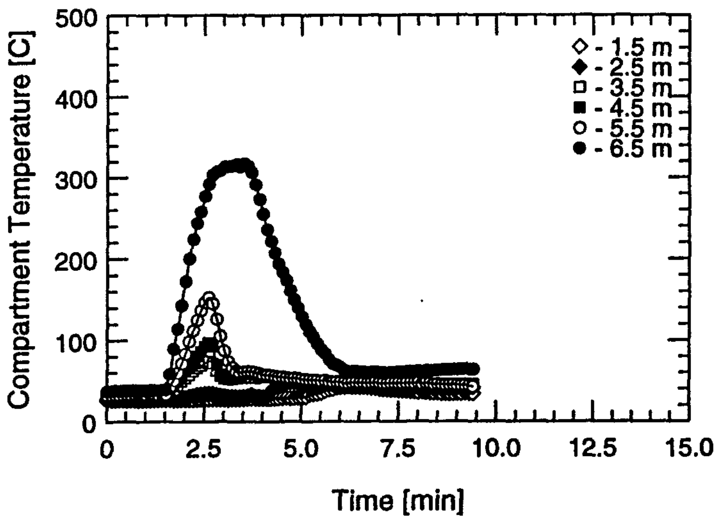
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

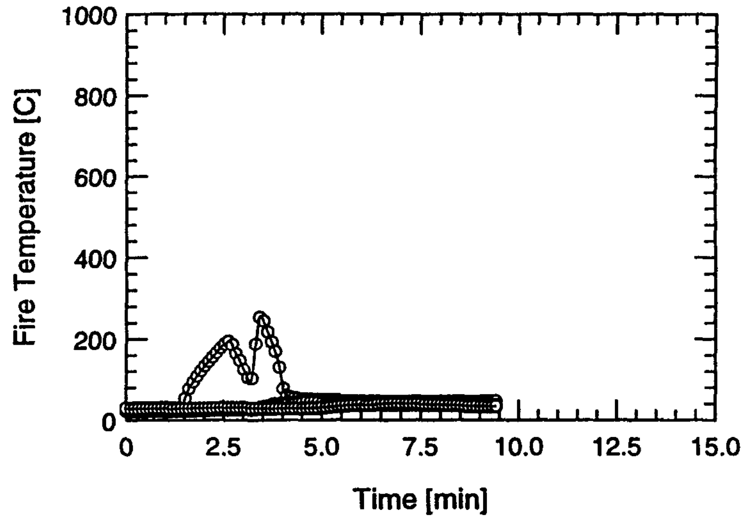
Test #111

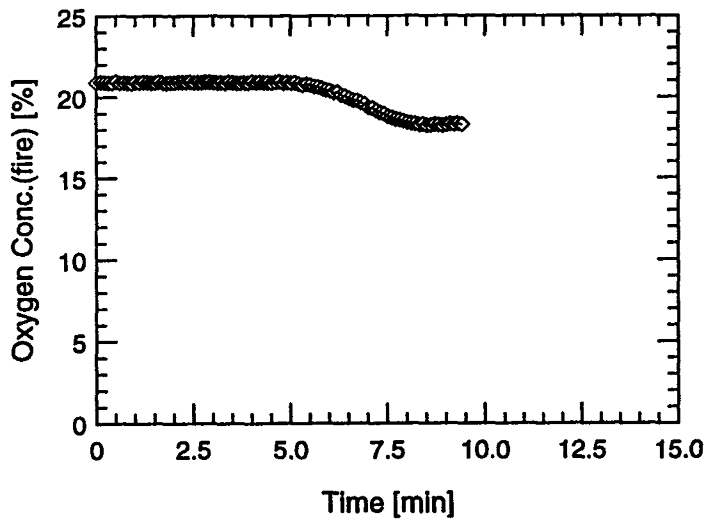


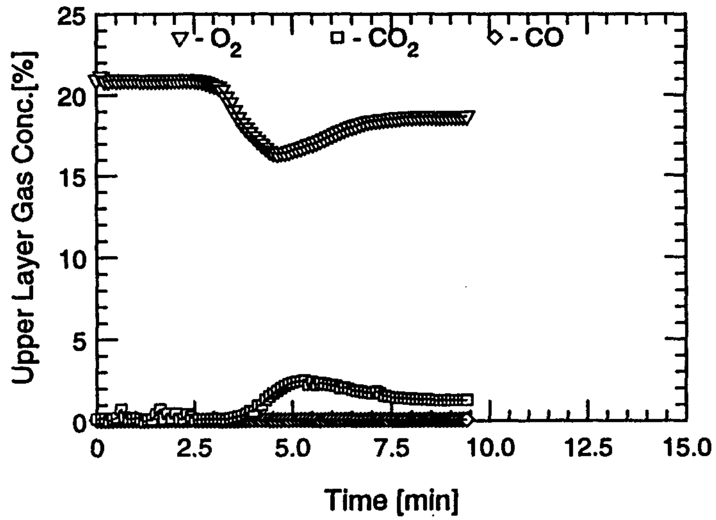
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #112

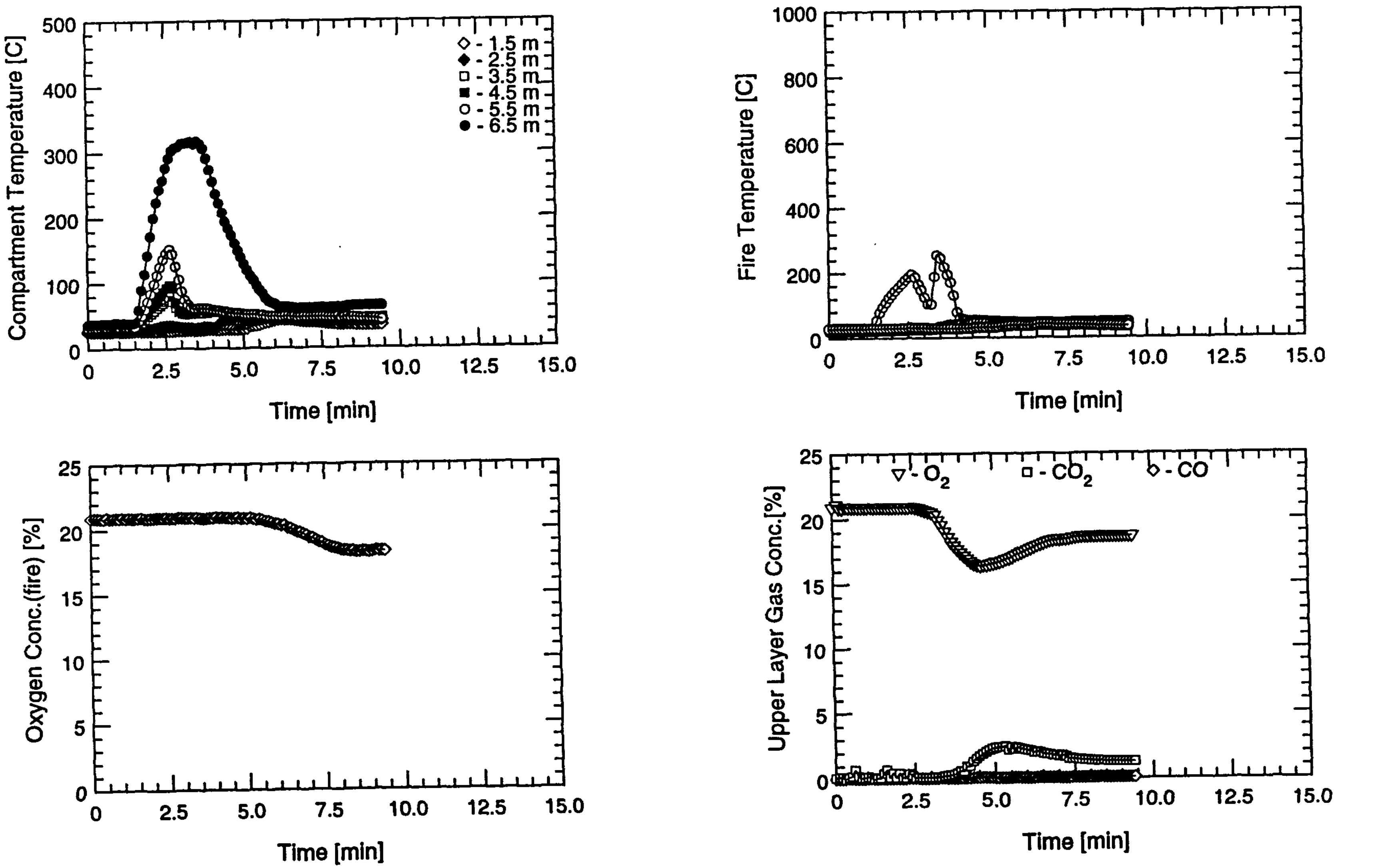

Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]


Fire Temperature [C]
1000
800
600
400
200
0
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]


Oxygen Conc.(fire) [%]
25
20
15
10
5
0
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]

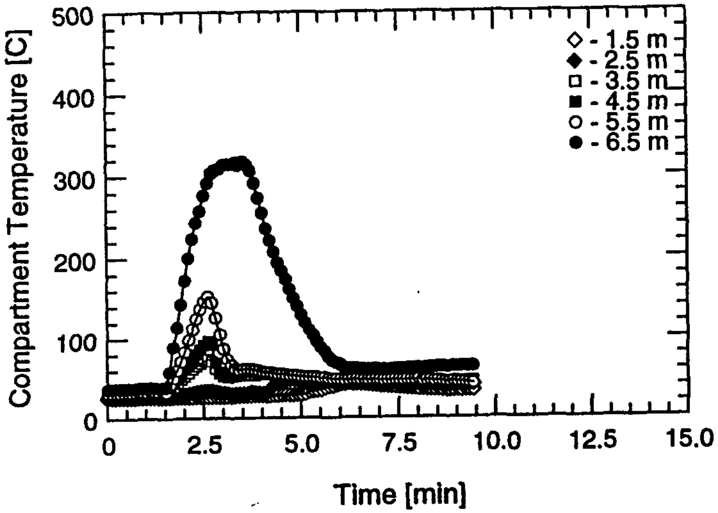

Upper Layer Gas Conc.[%]
25
20
15
10
5
0
▽ - O2
□ - CO2
◇ - CO
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]

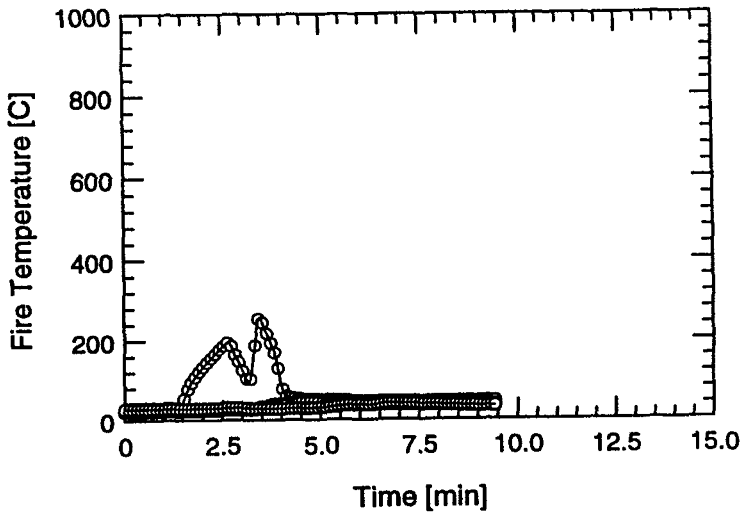
Test #113

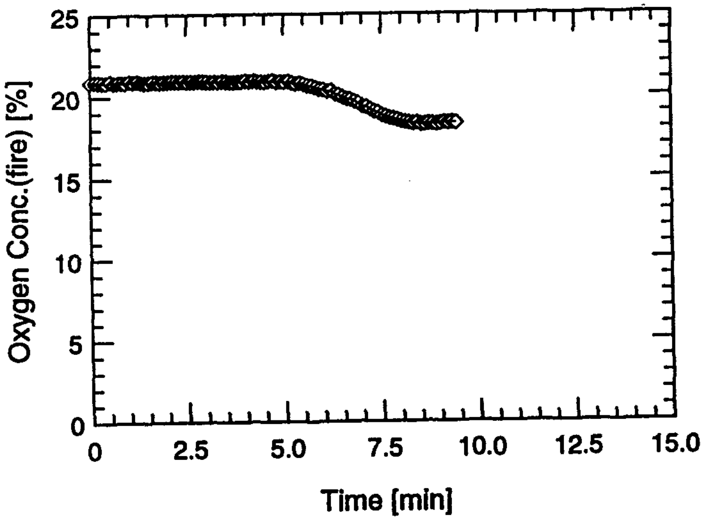


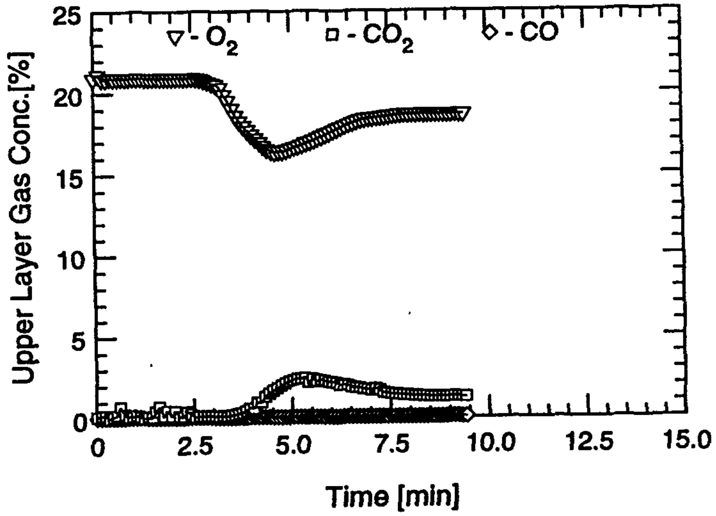
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #114

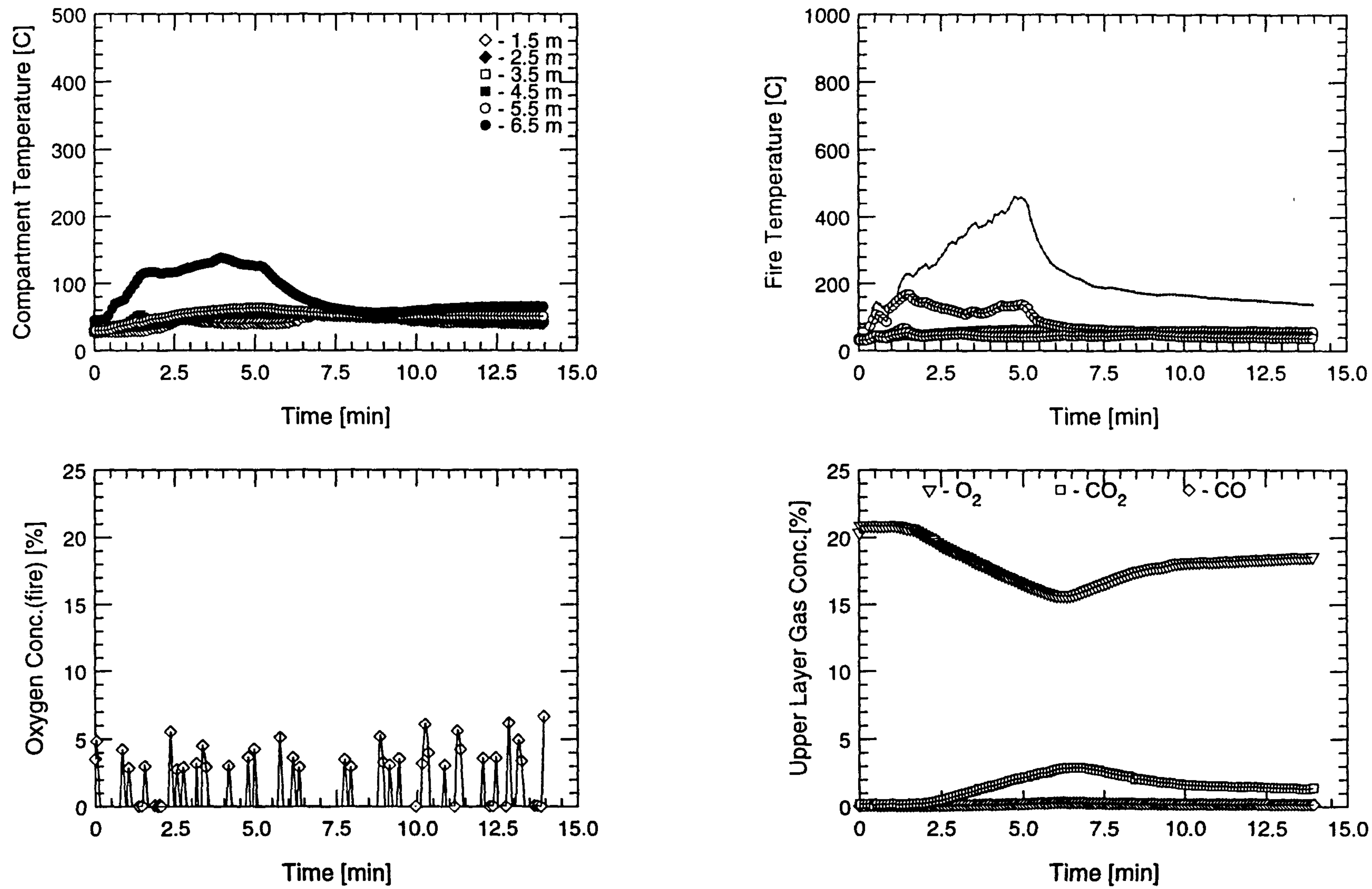

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m


Fire Temperature [C]
Time [min]


Oxygen Conc.(fire) [%]
Time [min]

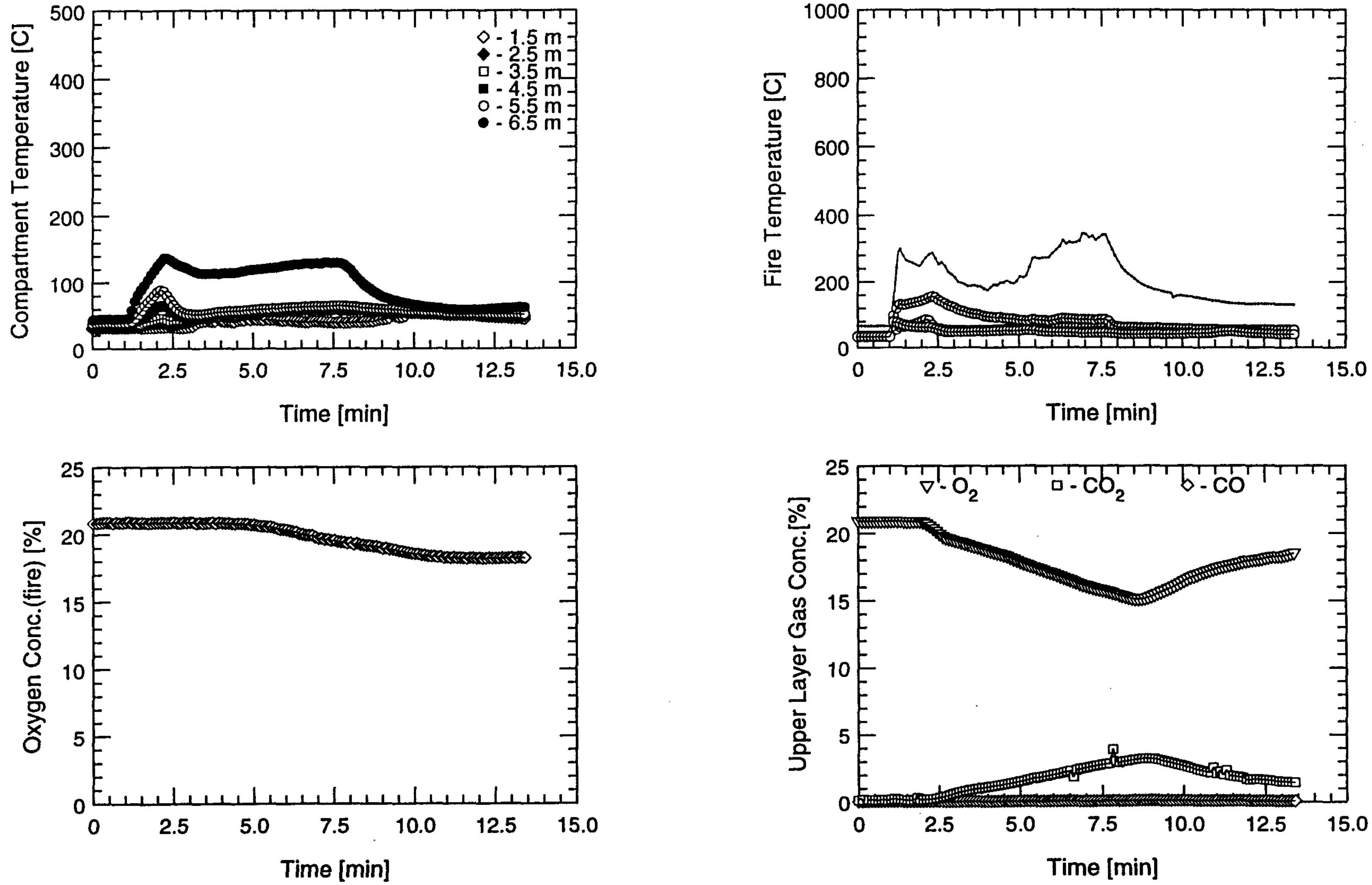

Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #115



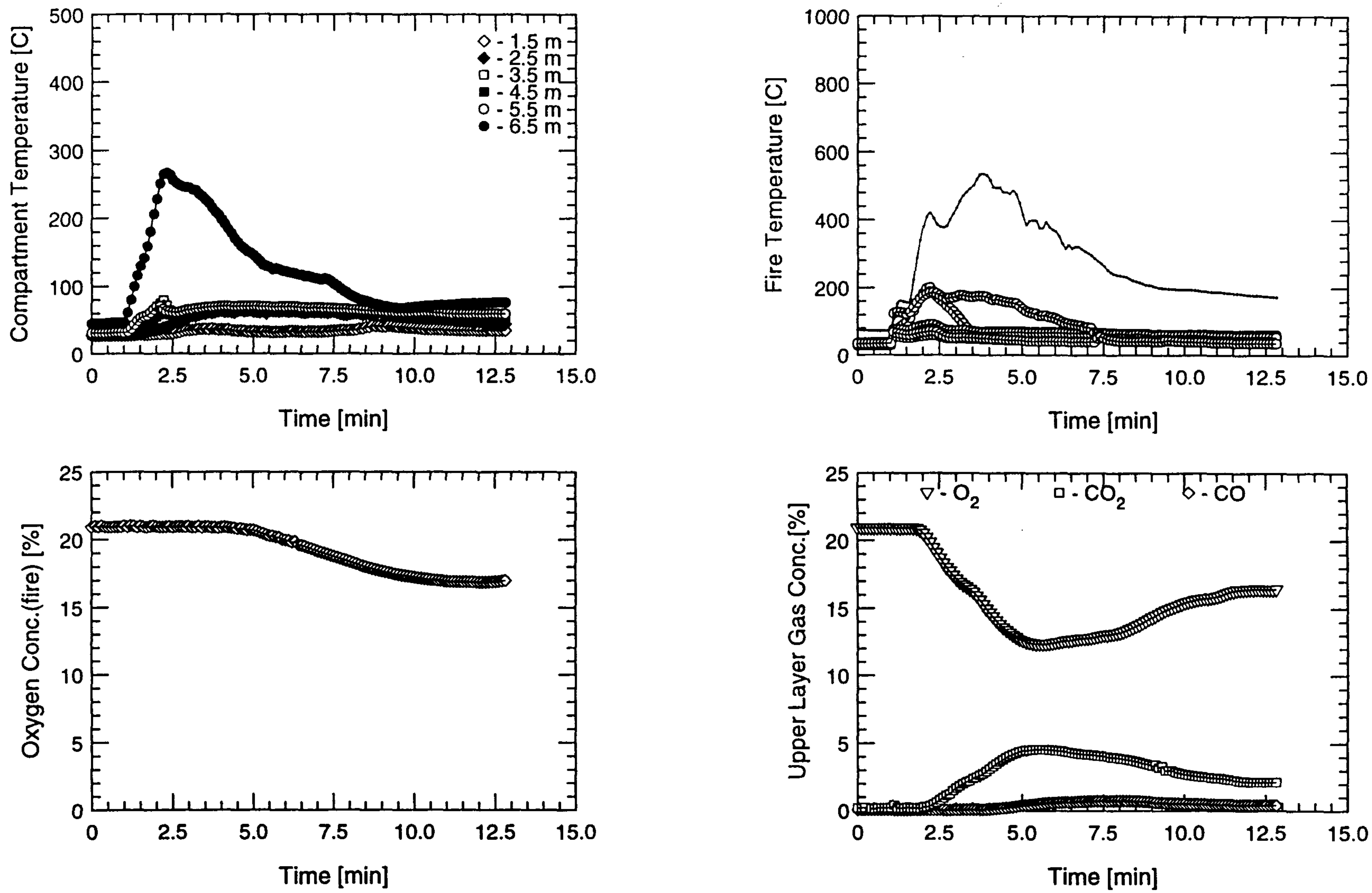
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #116

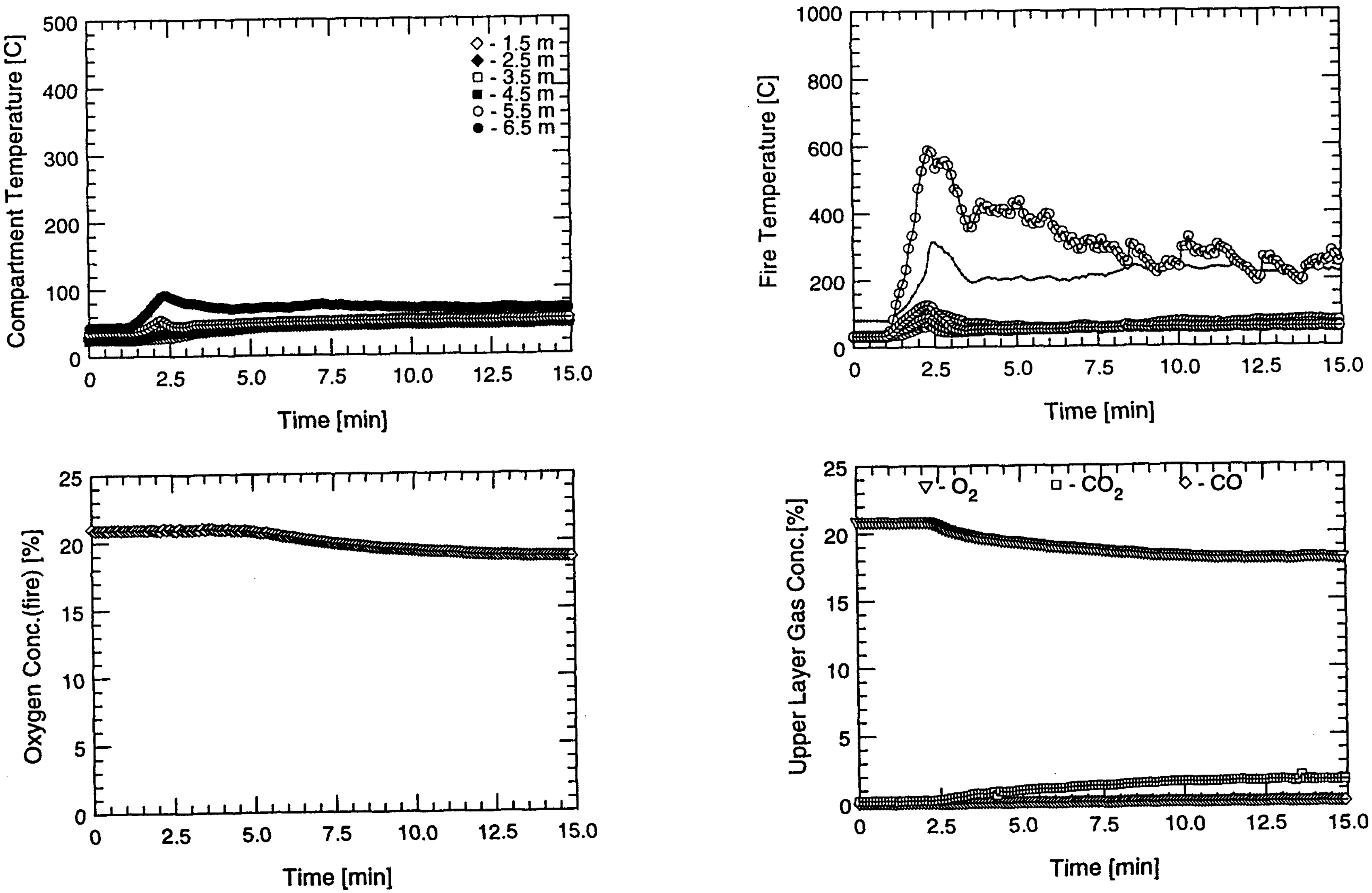


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #117

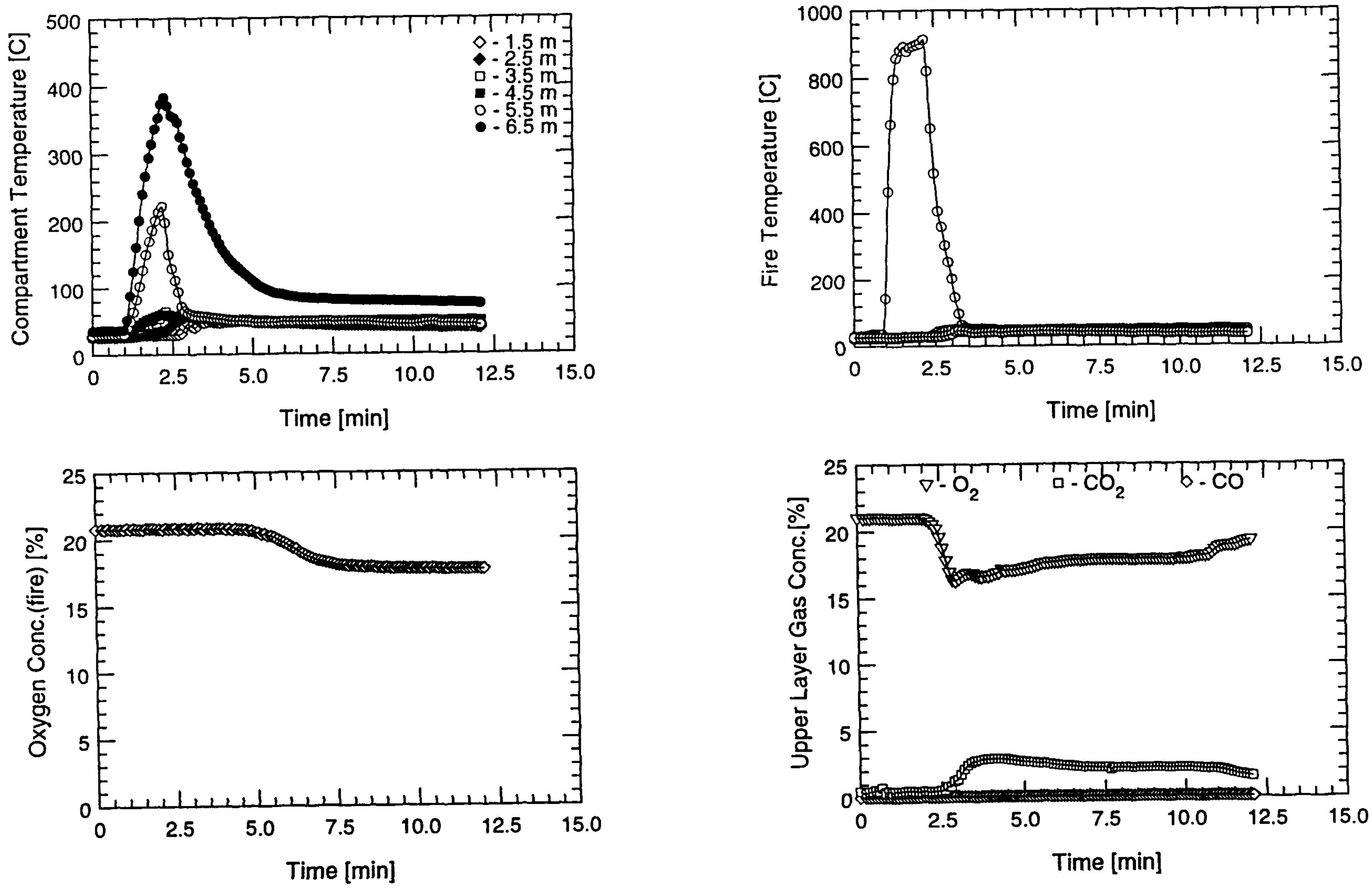

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #118

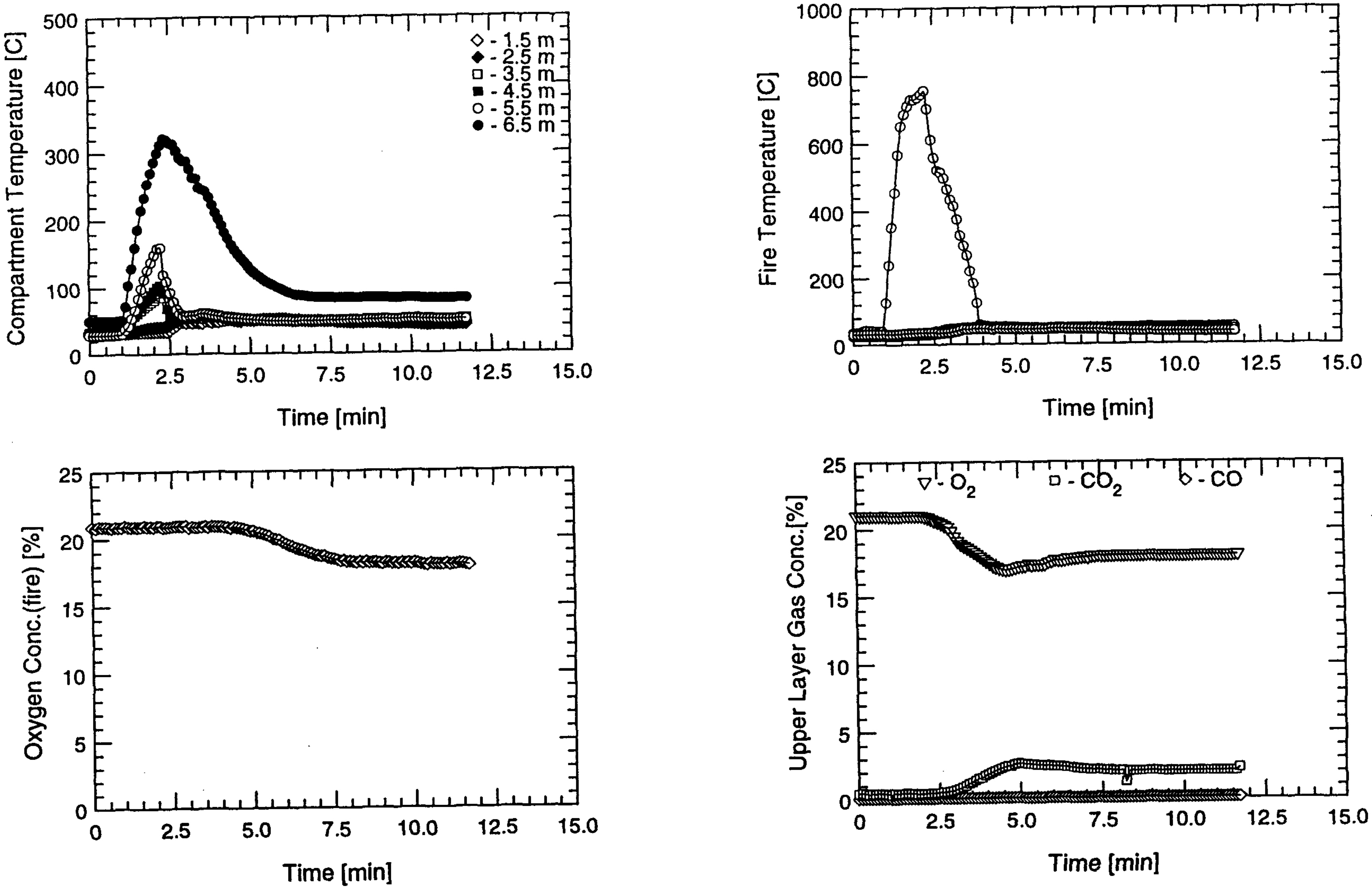


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #119

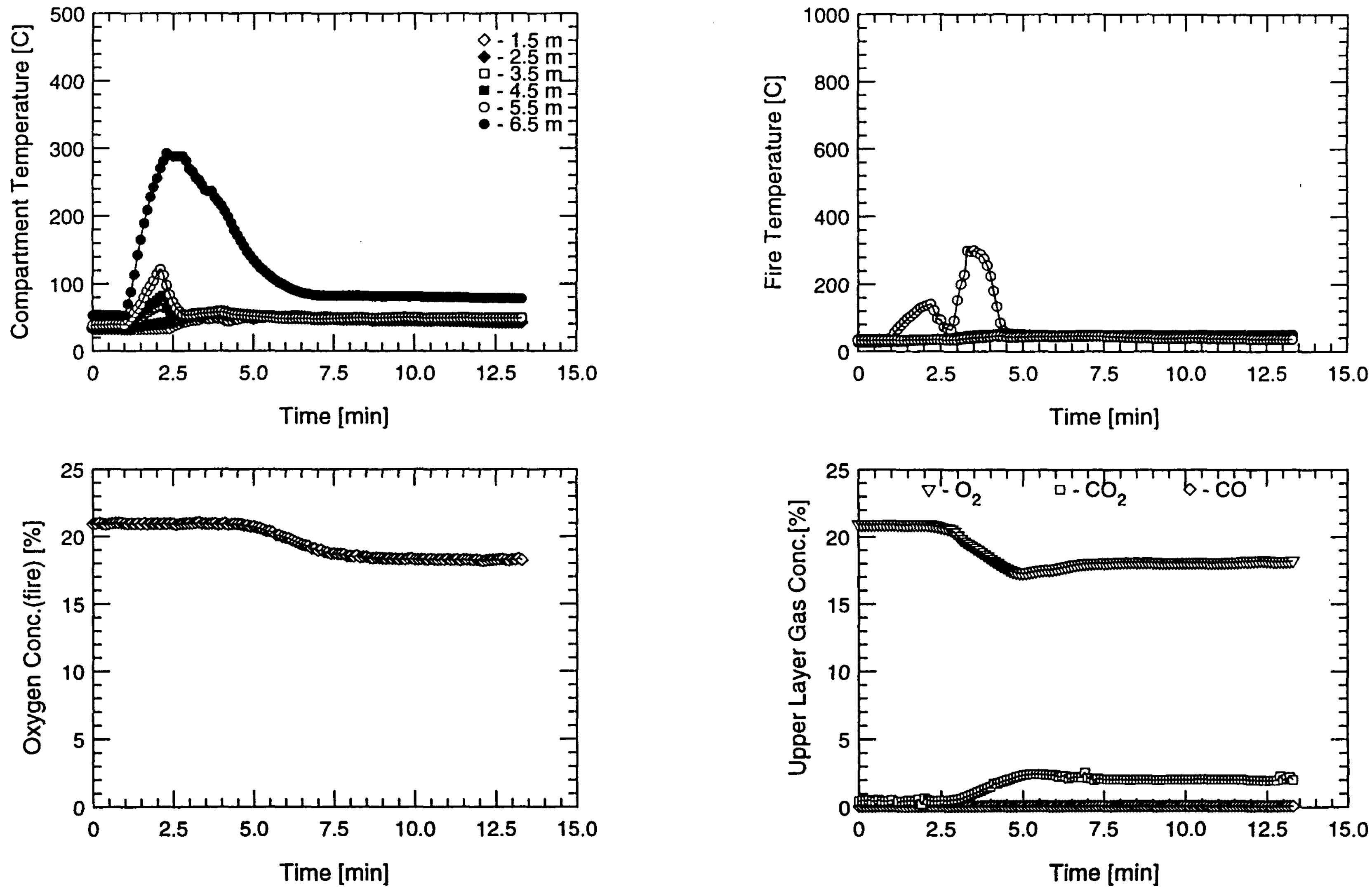

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #120

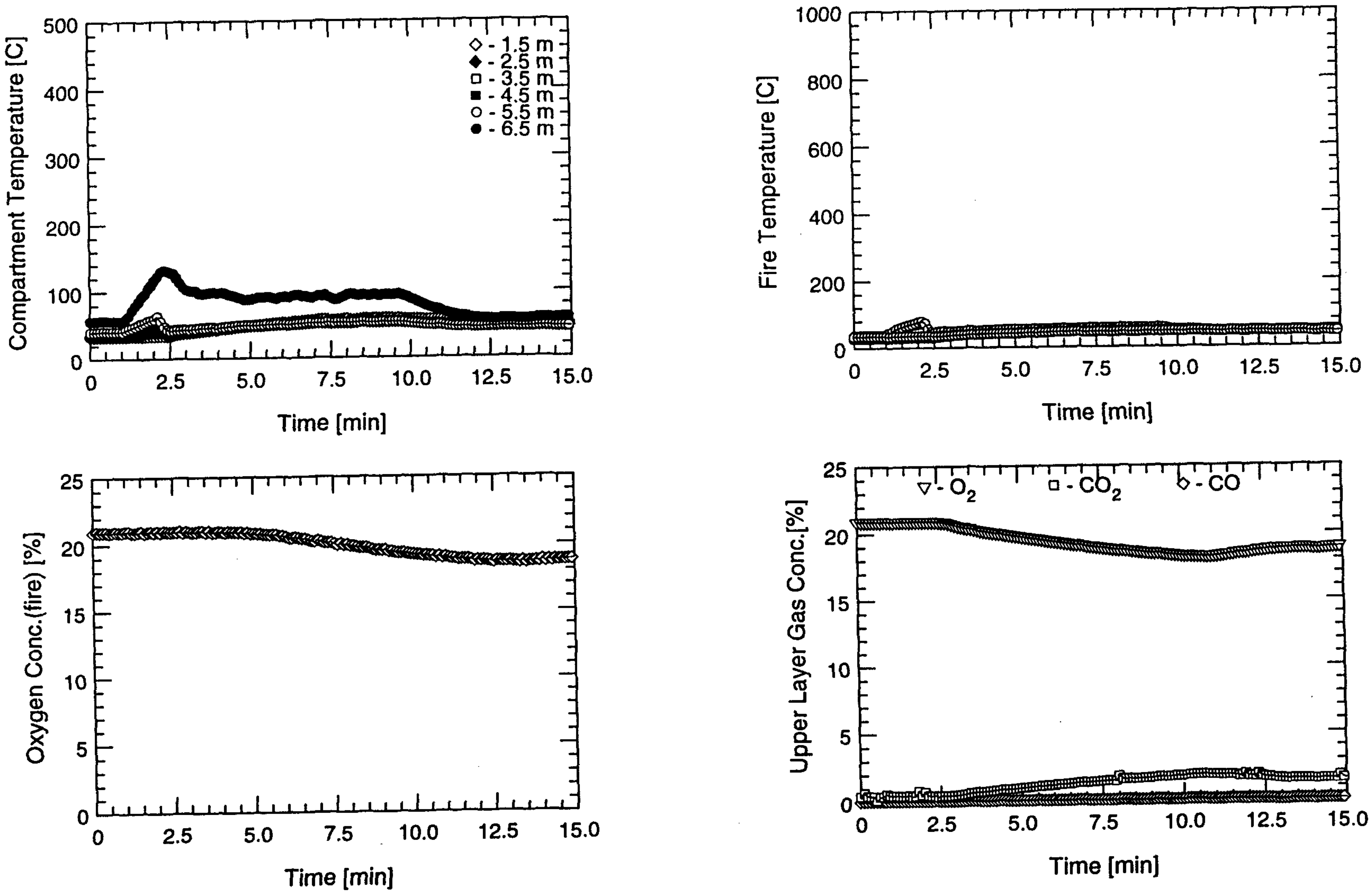


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

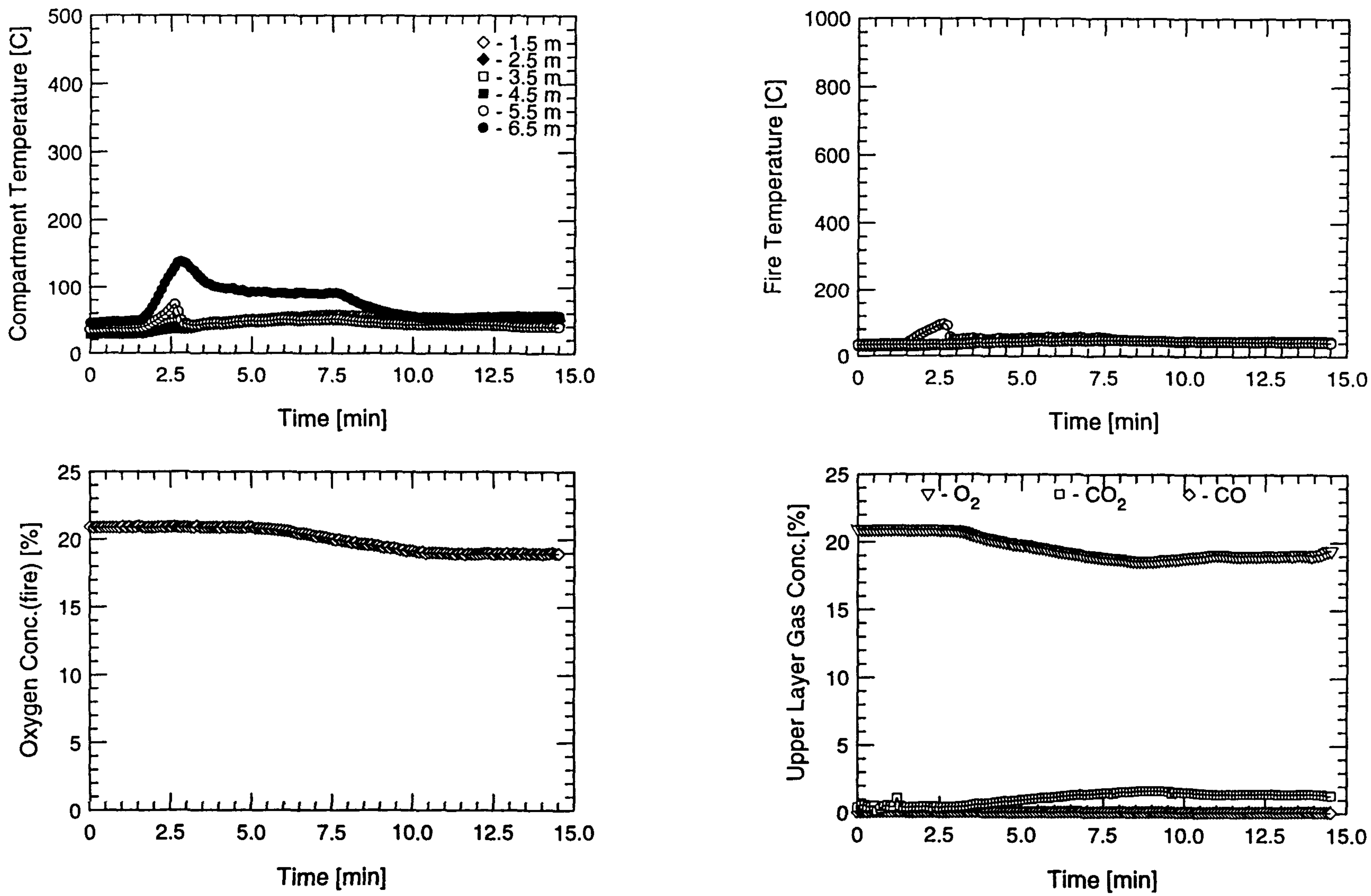
Test #121


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #122

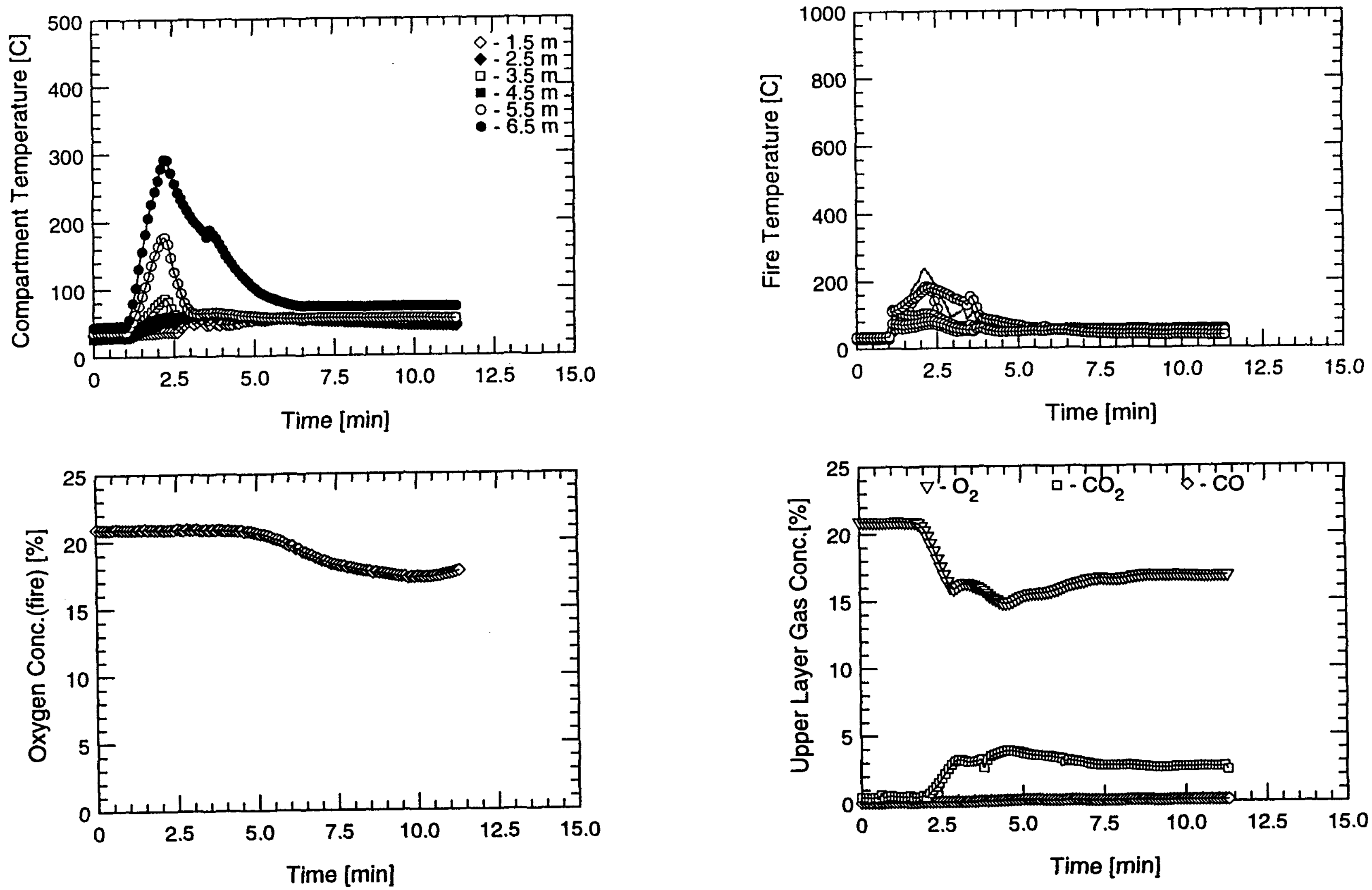

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #123

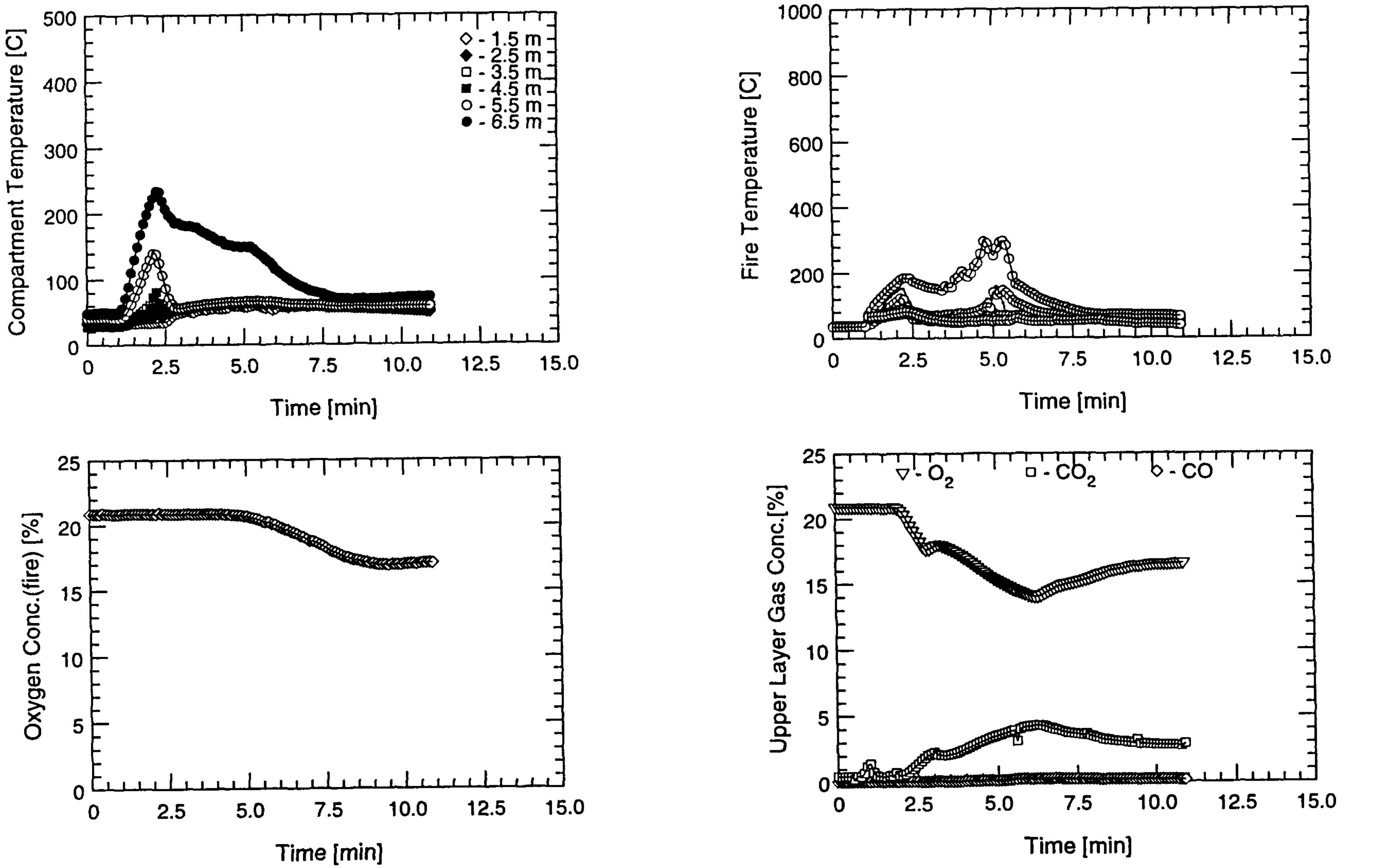


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #124

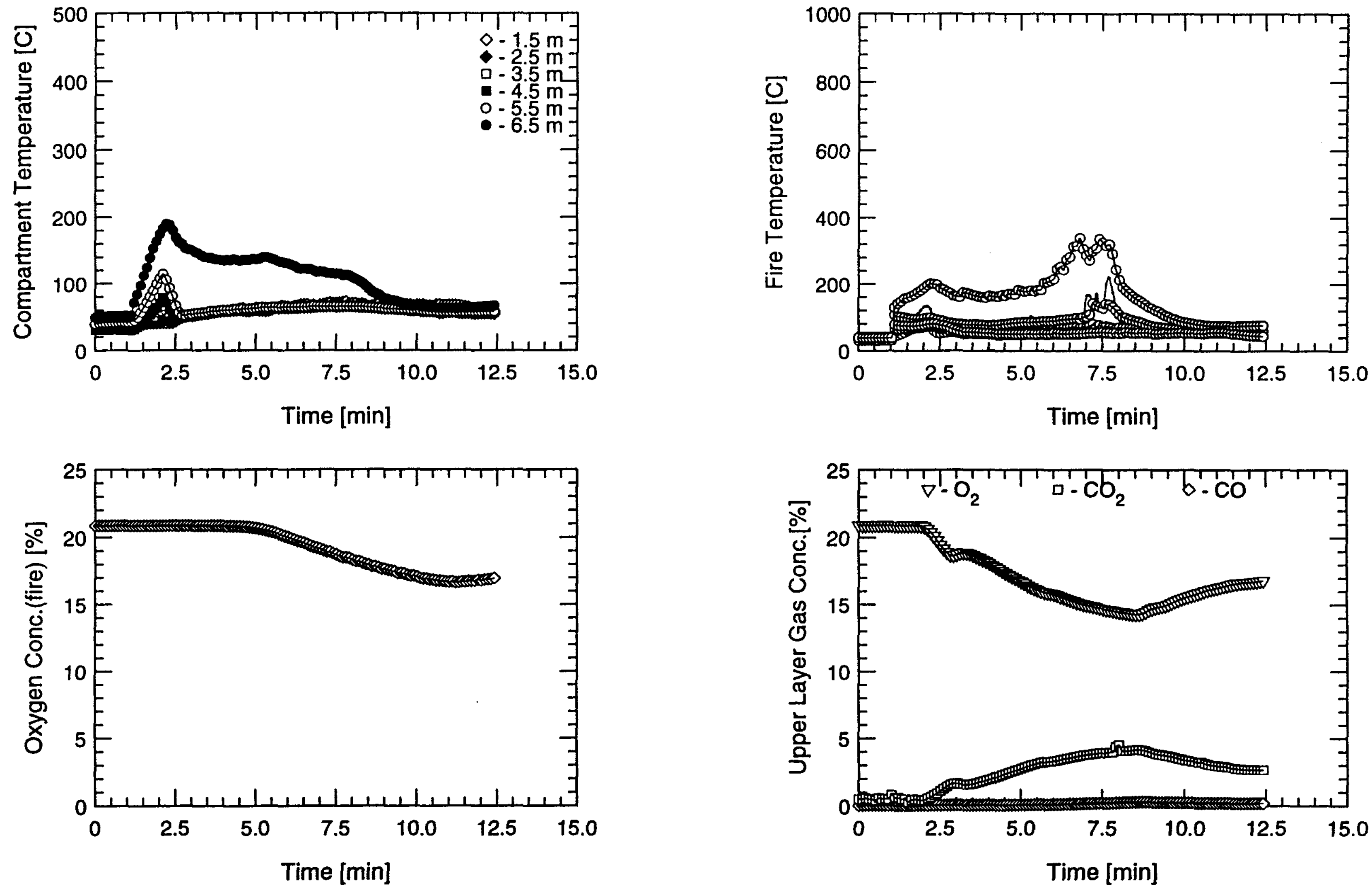

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #125



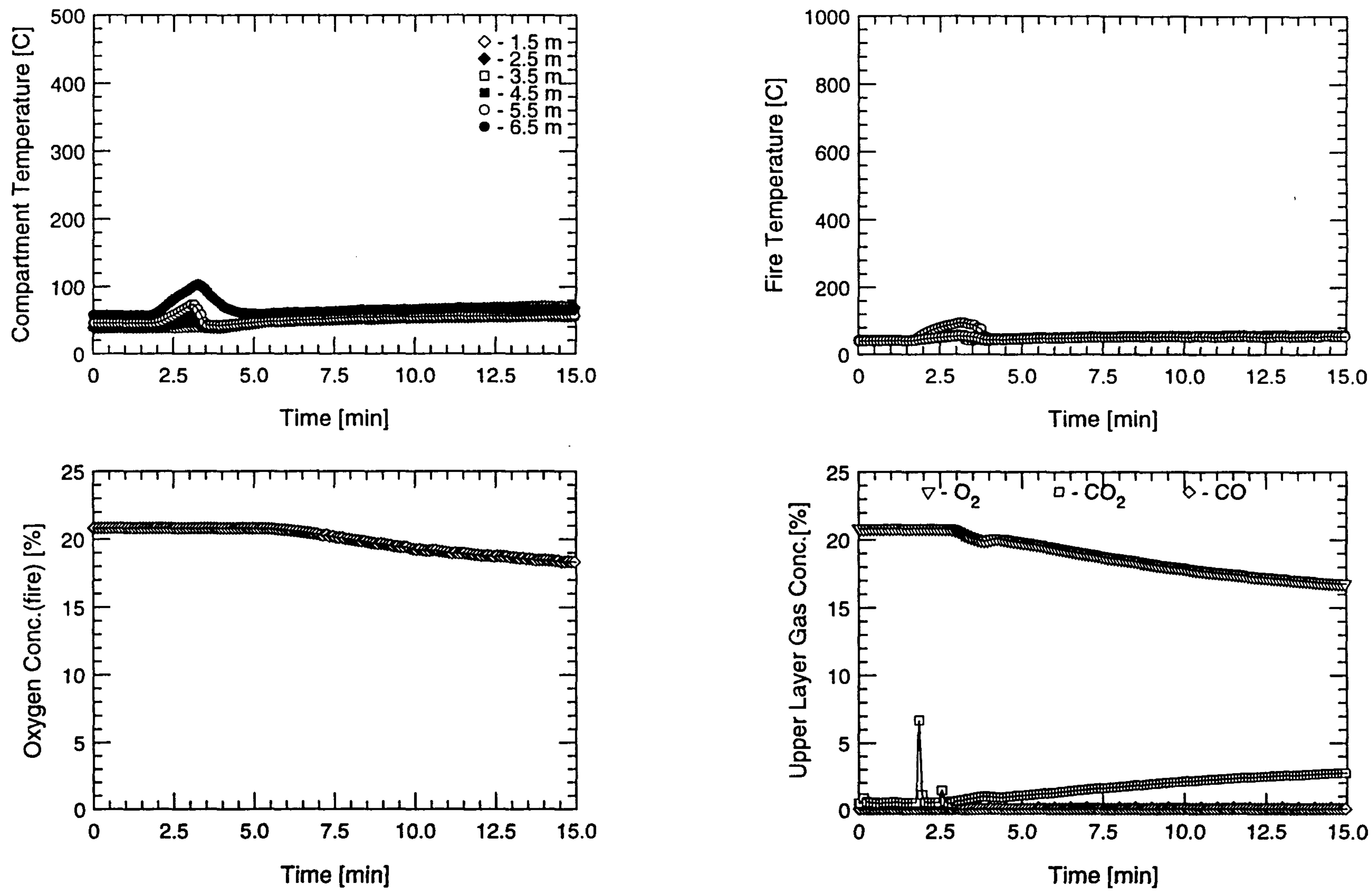
Compartment Temperature [C]
500
400
300
200
100
0
Time [min]
0
2.5
5.0
7.5
10.0
12.5
15.0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #126

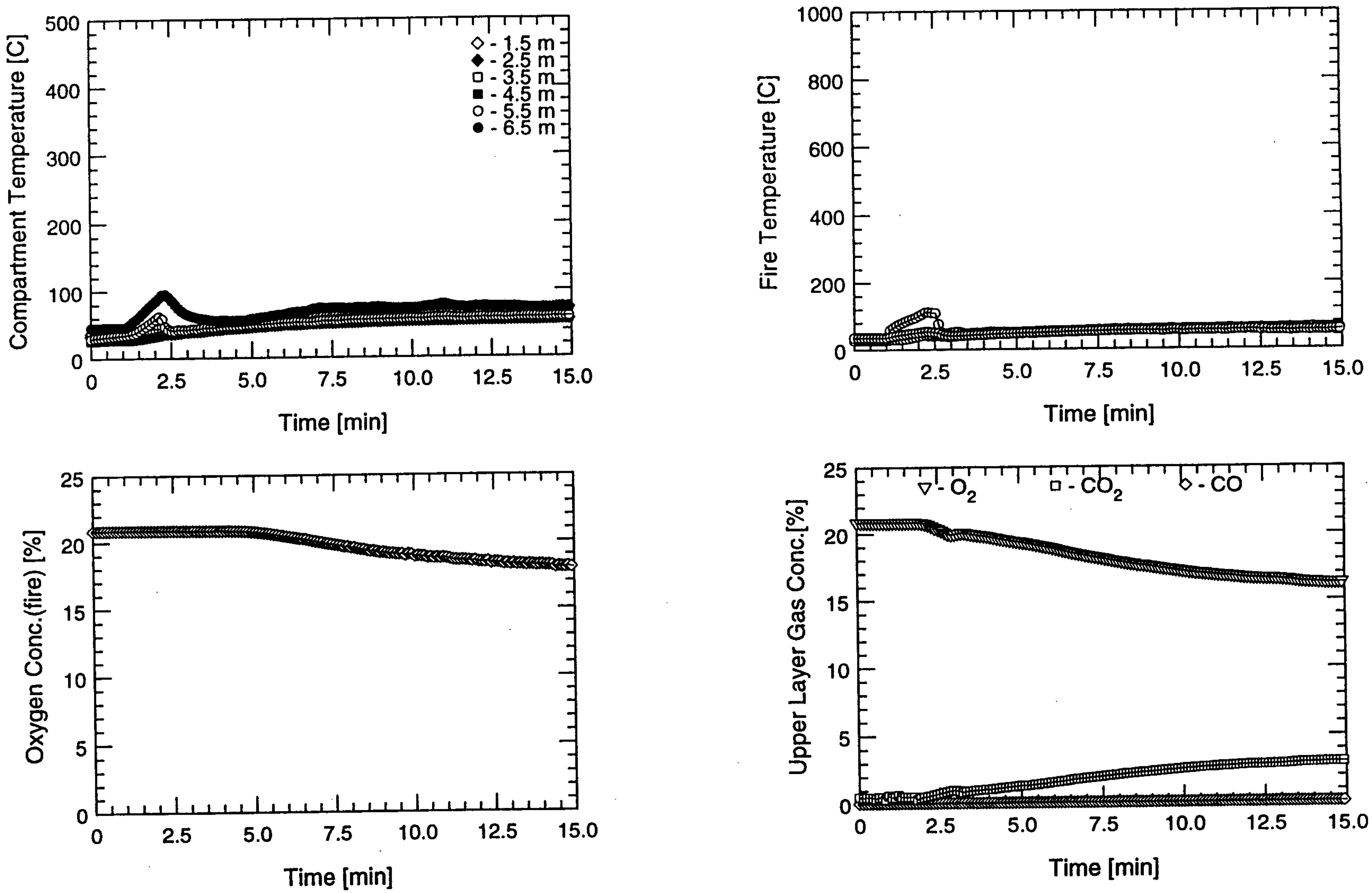


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

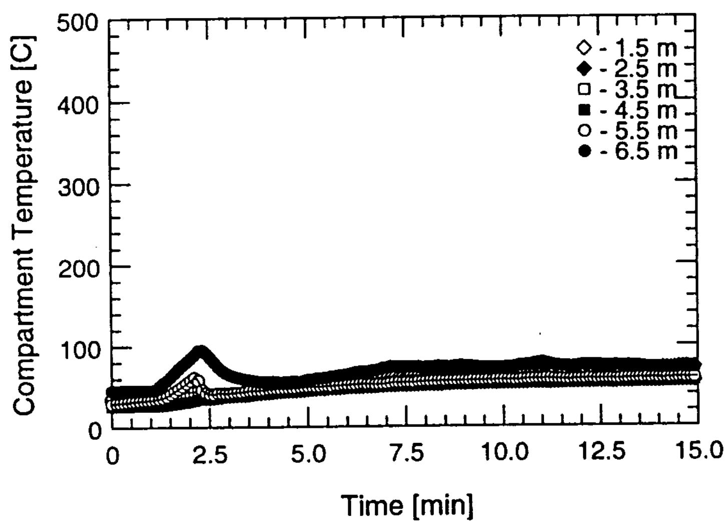
Test #127


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

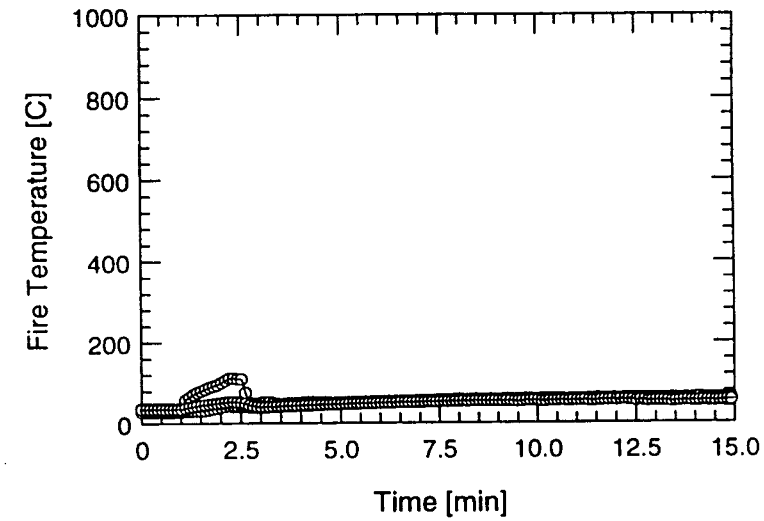
Test #128


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

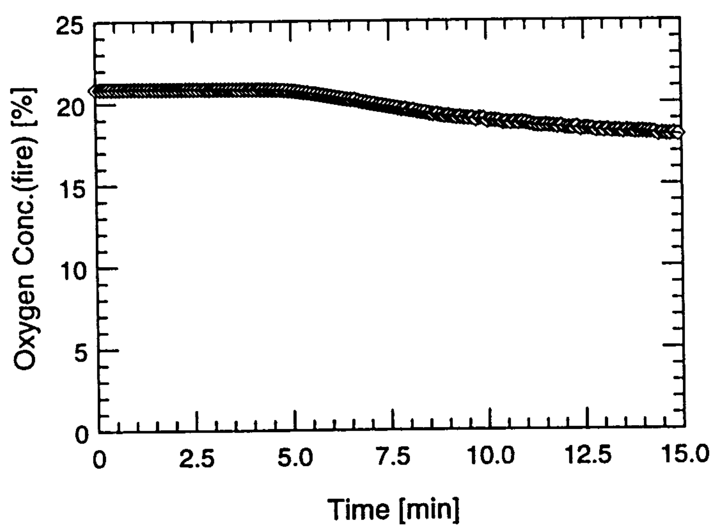
Test #129



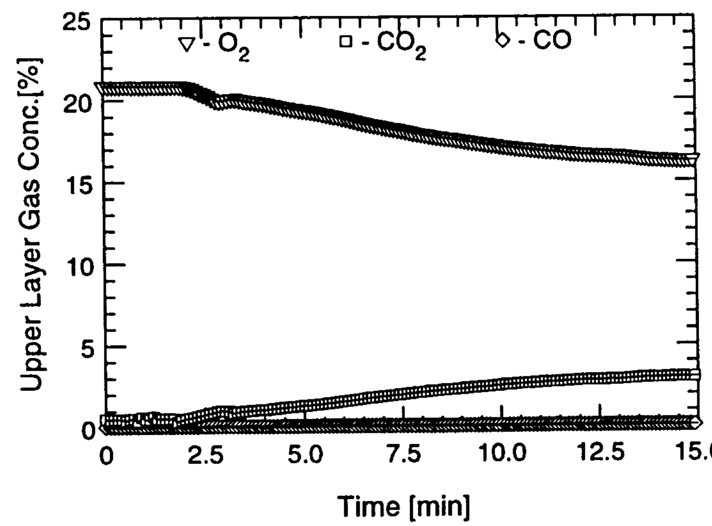
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]



Fire Temperature [C]
Time [min]

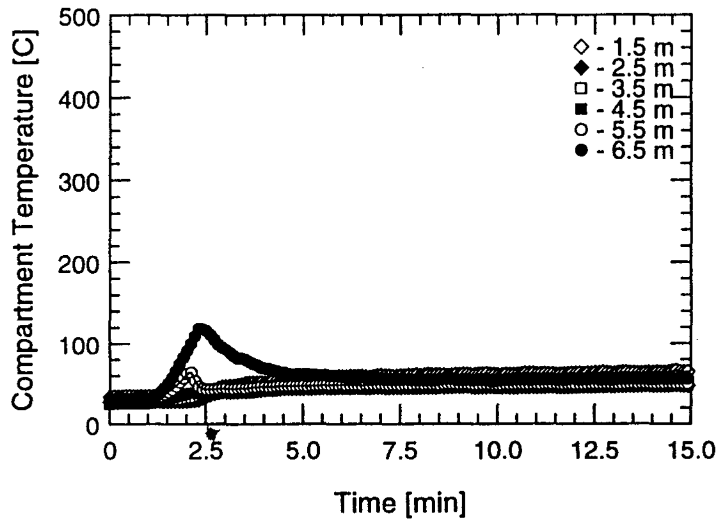


Oxygen Conc.(fire) [%]
Time [min]

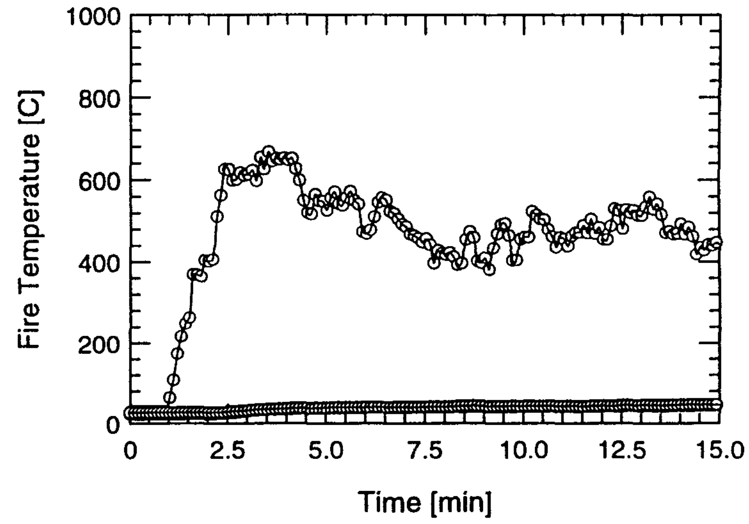


Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

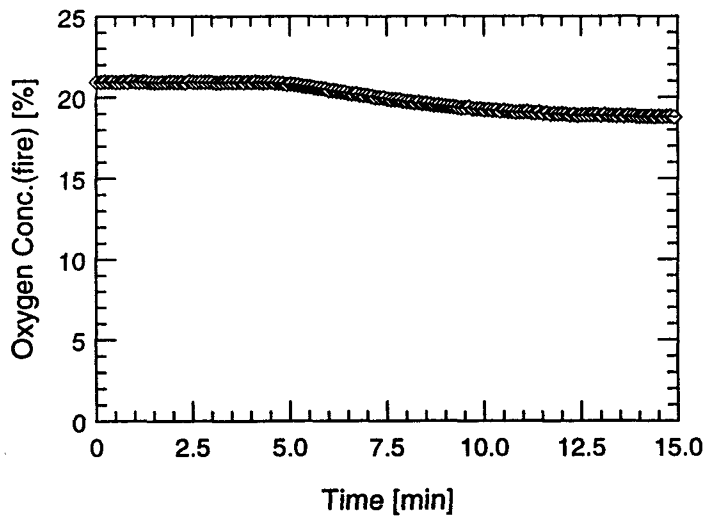
Test #130



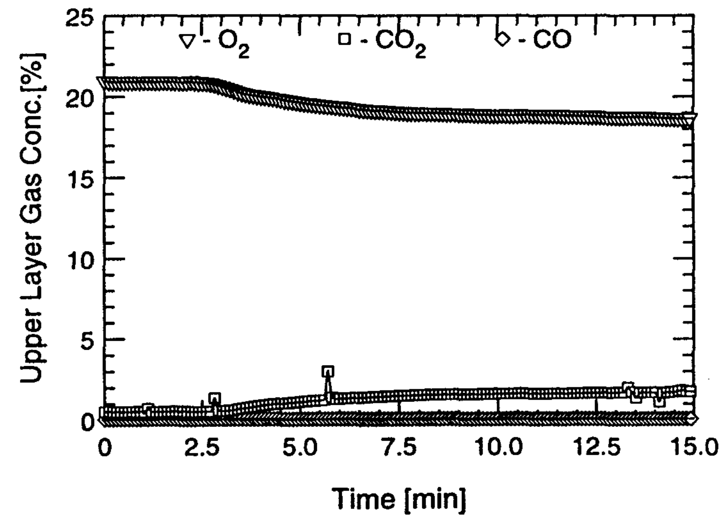
Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m



Fire Temperature [C]
Time [min]

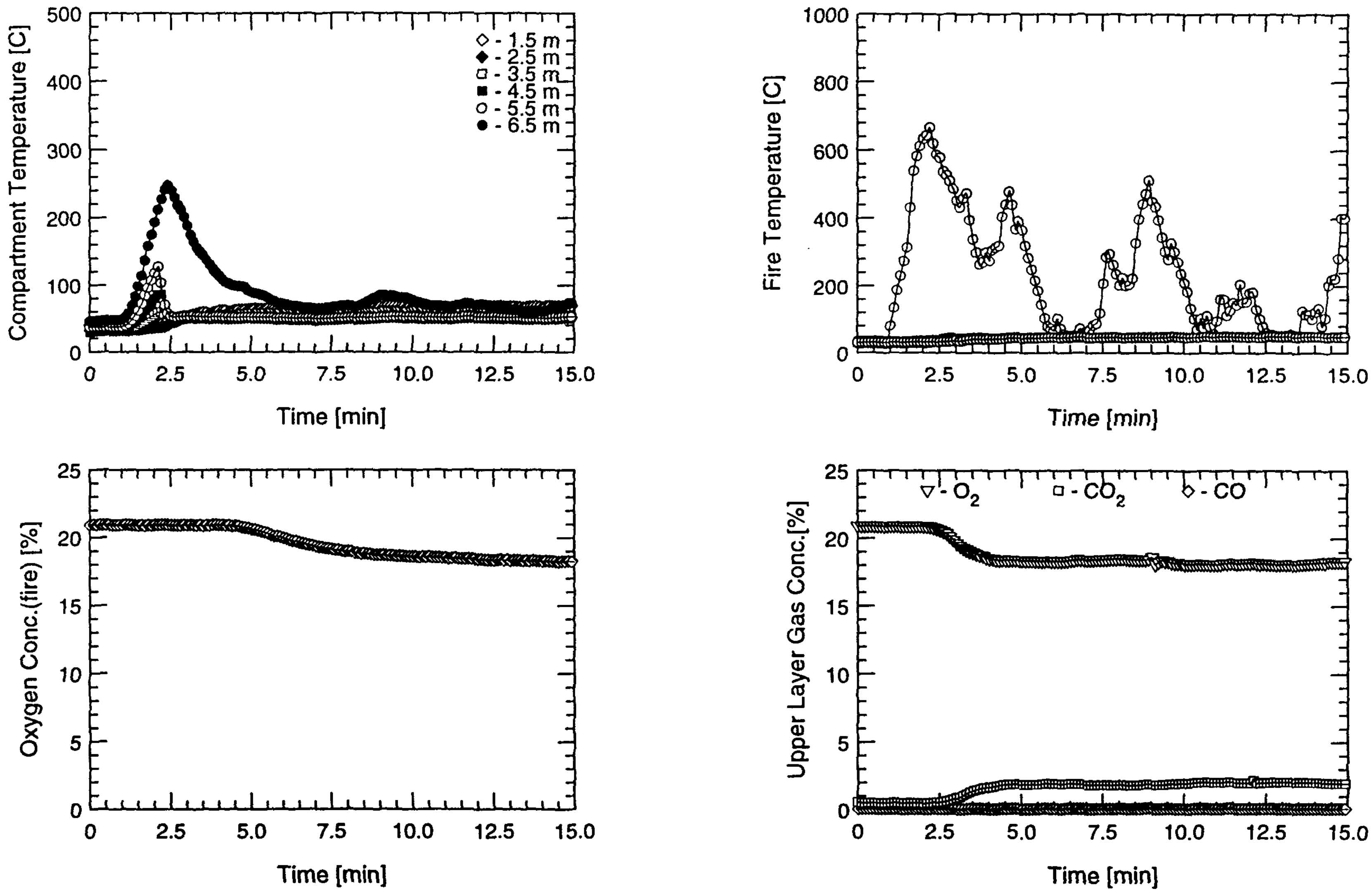


Oxygen Conc.(fire) [%]
Time [min]



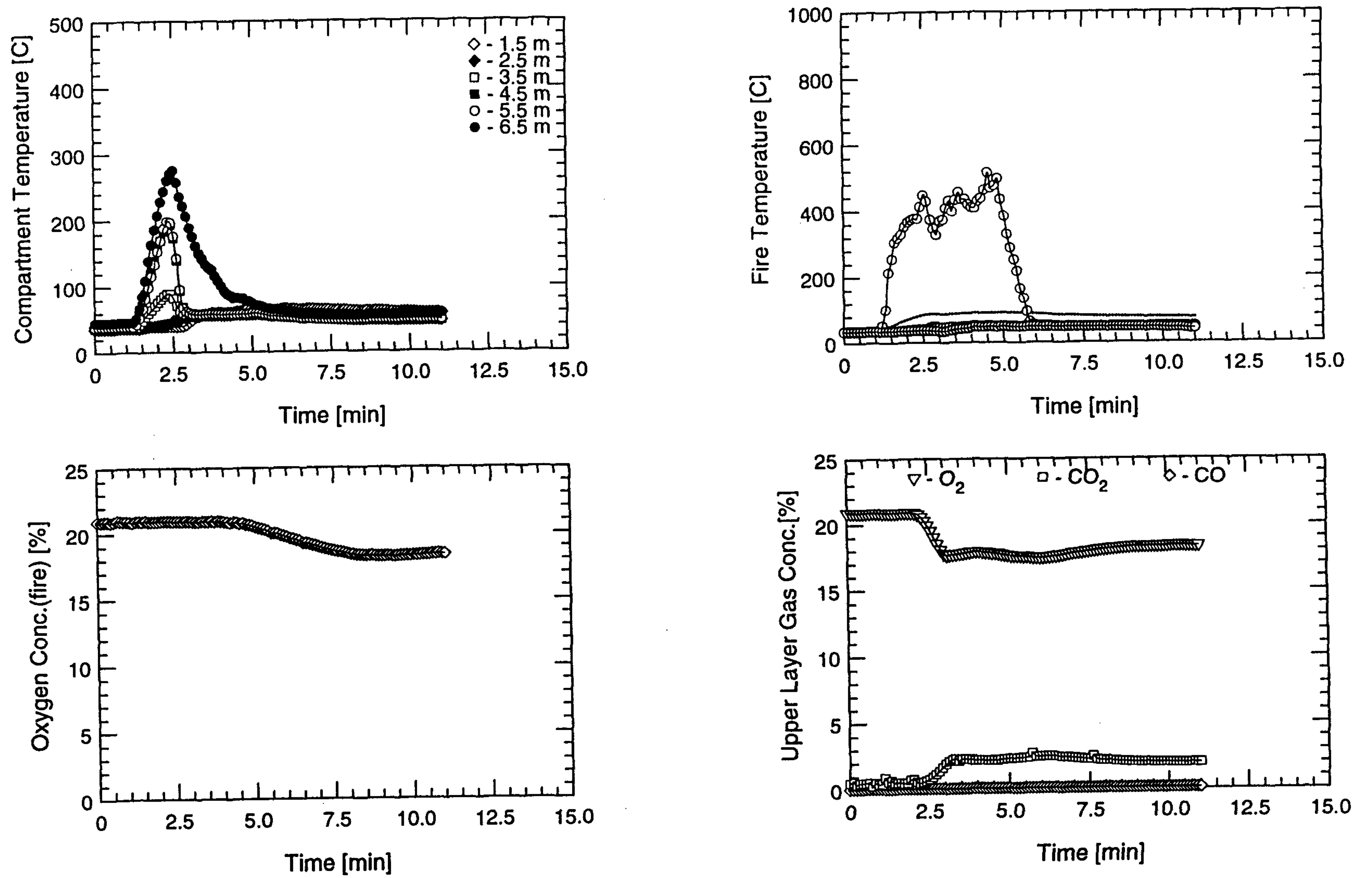
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #131

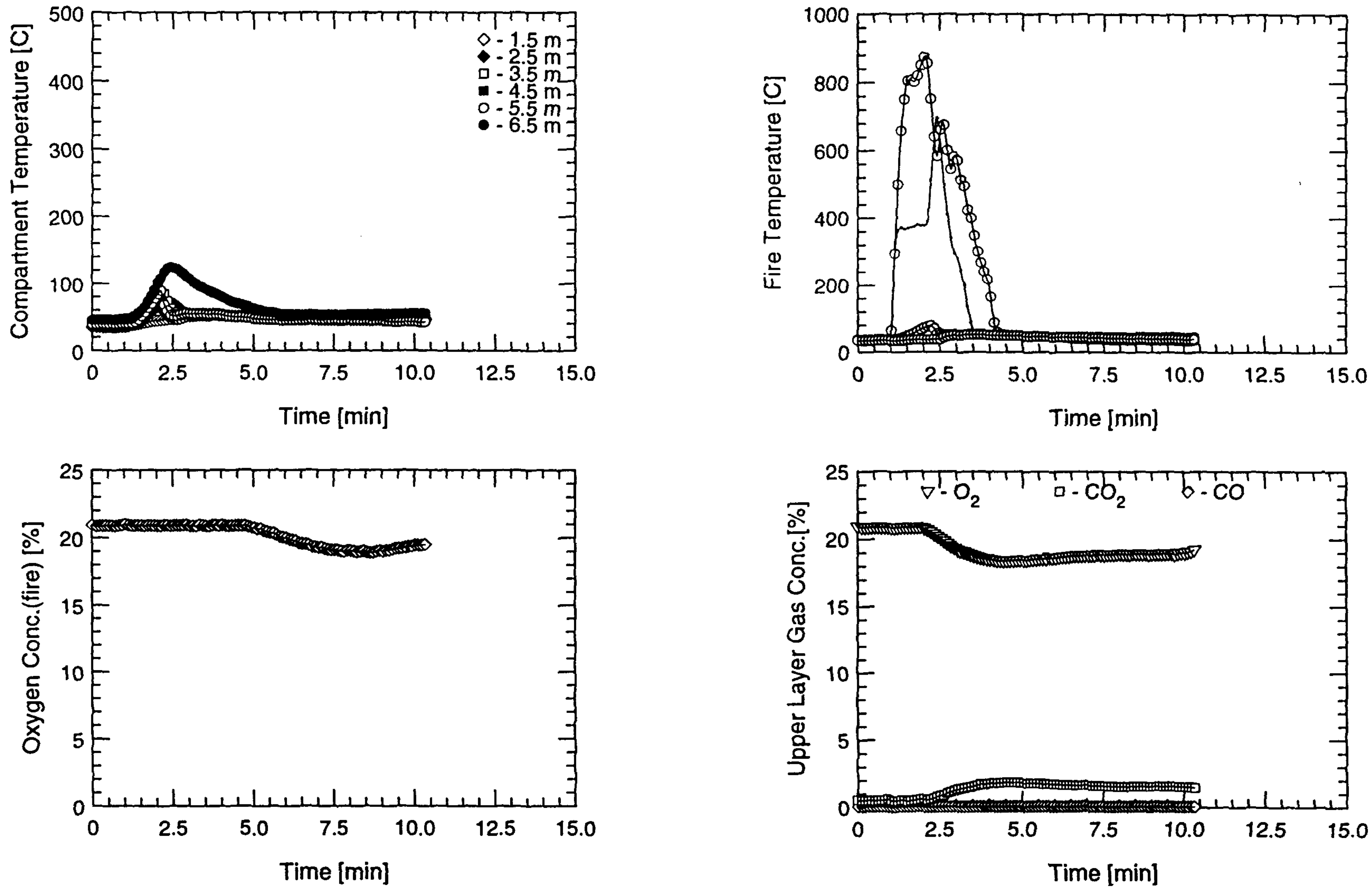


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #132

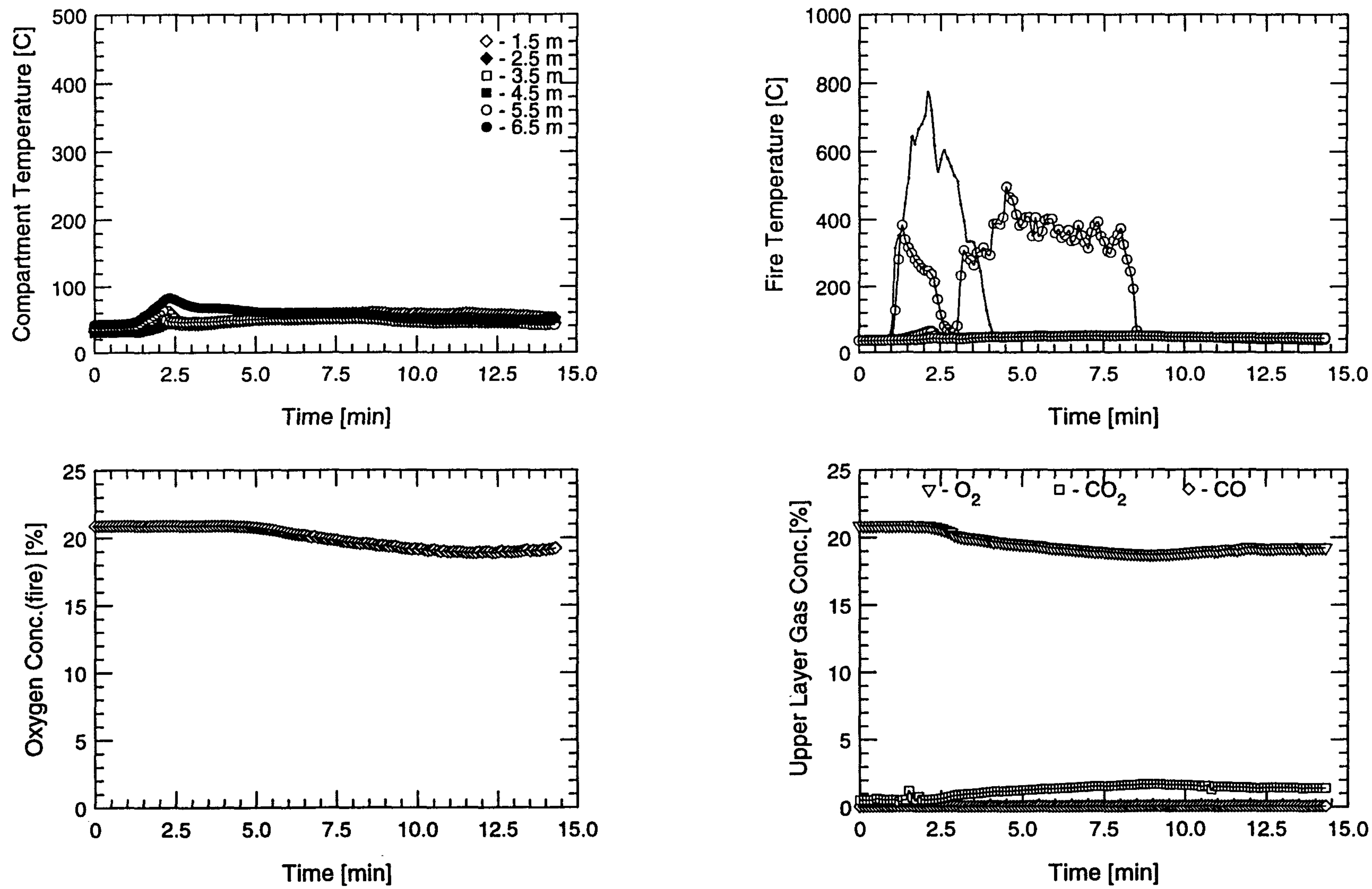

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #133



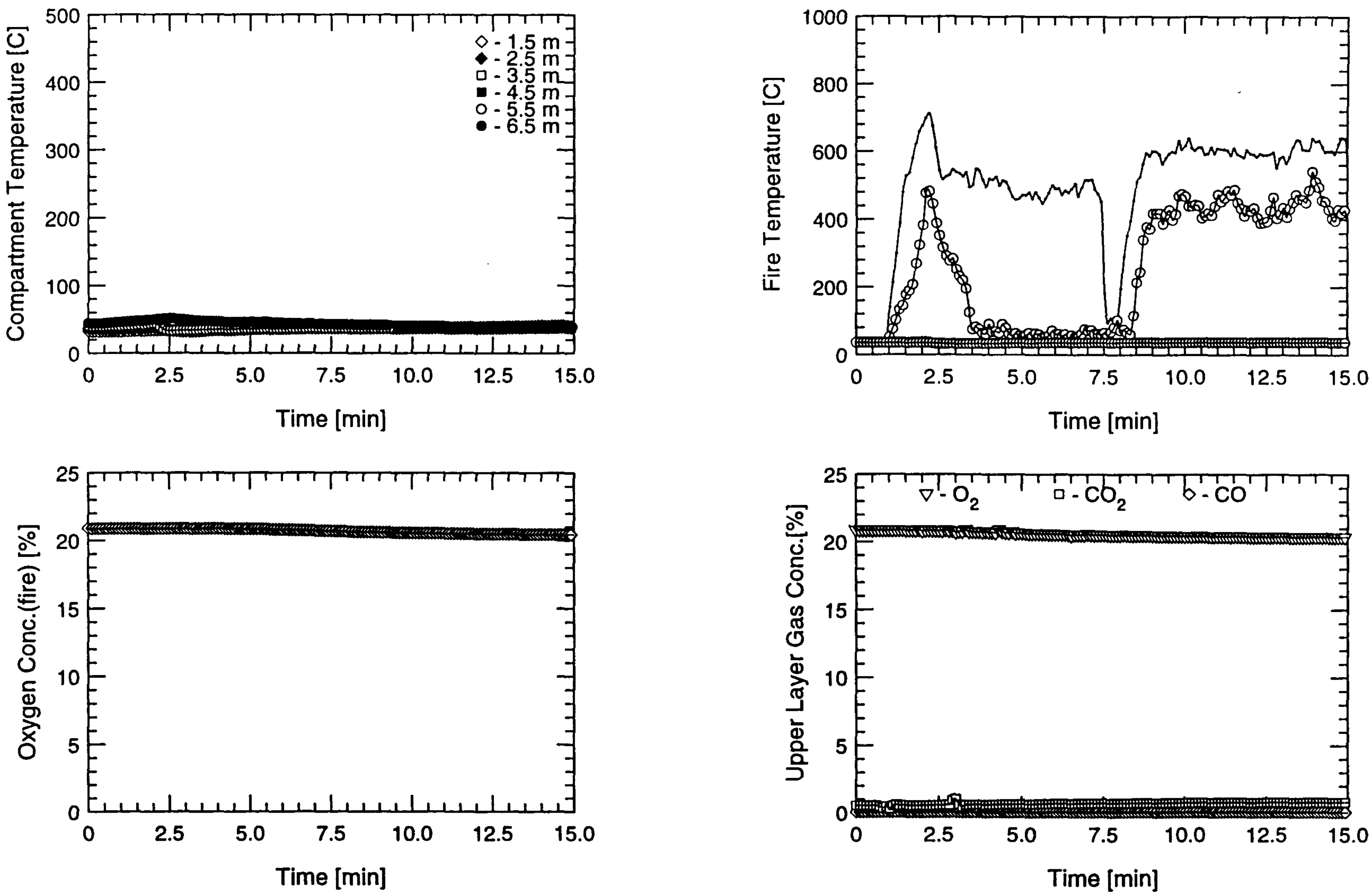
Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #134

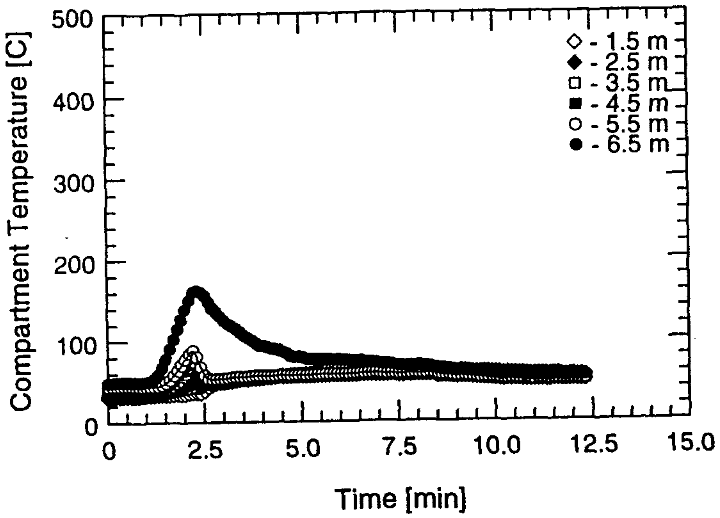


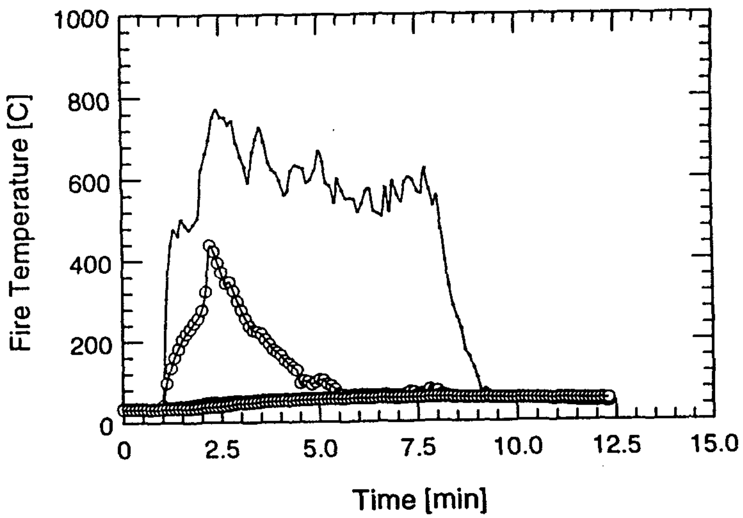
Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
0
2.5
5.0
7.5
10.0
12.5
15.0
Fire Temperature [C]
1000
800
600
400
200
Oxygen Conc.(fire) [%]
25
20
15
10
5
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO

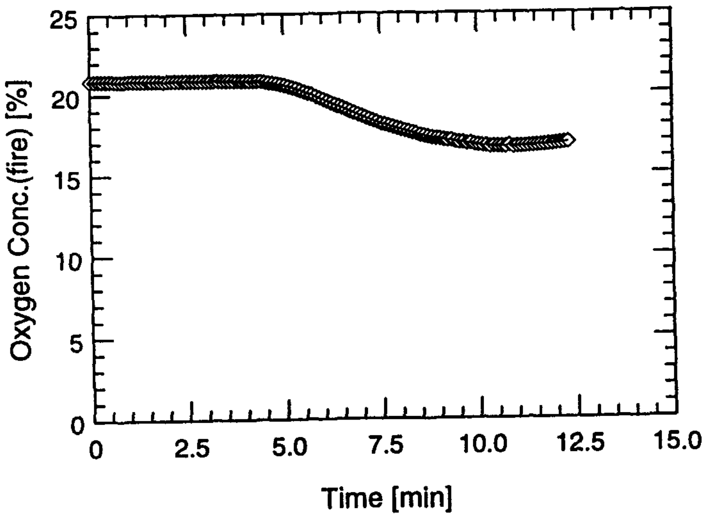
Test #135

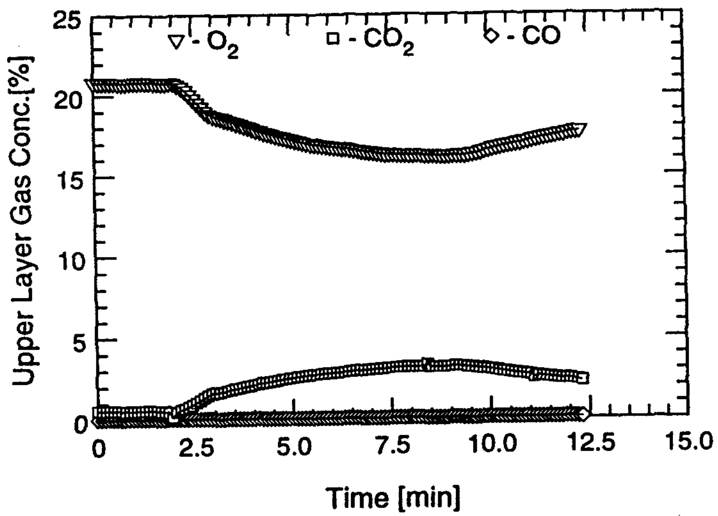

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #136

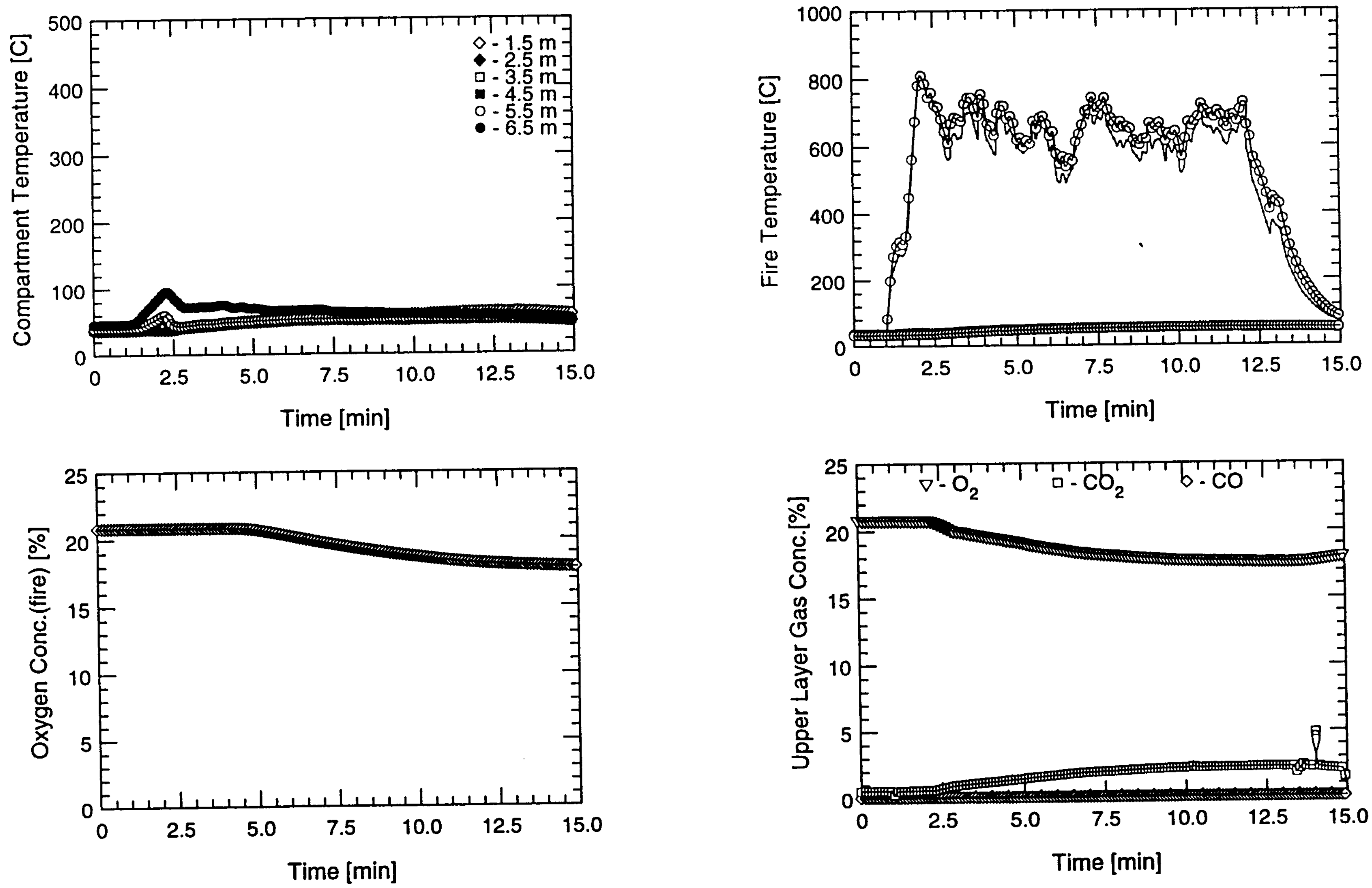

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m


Fire Temperature [C]
Time [min]

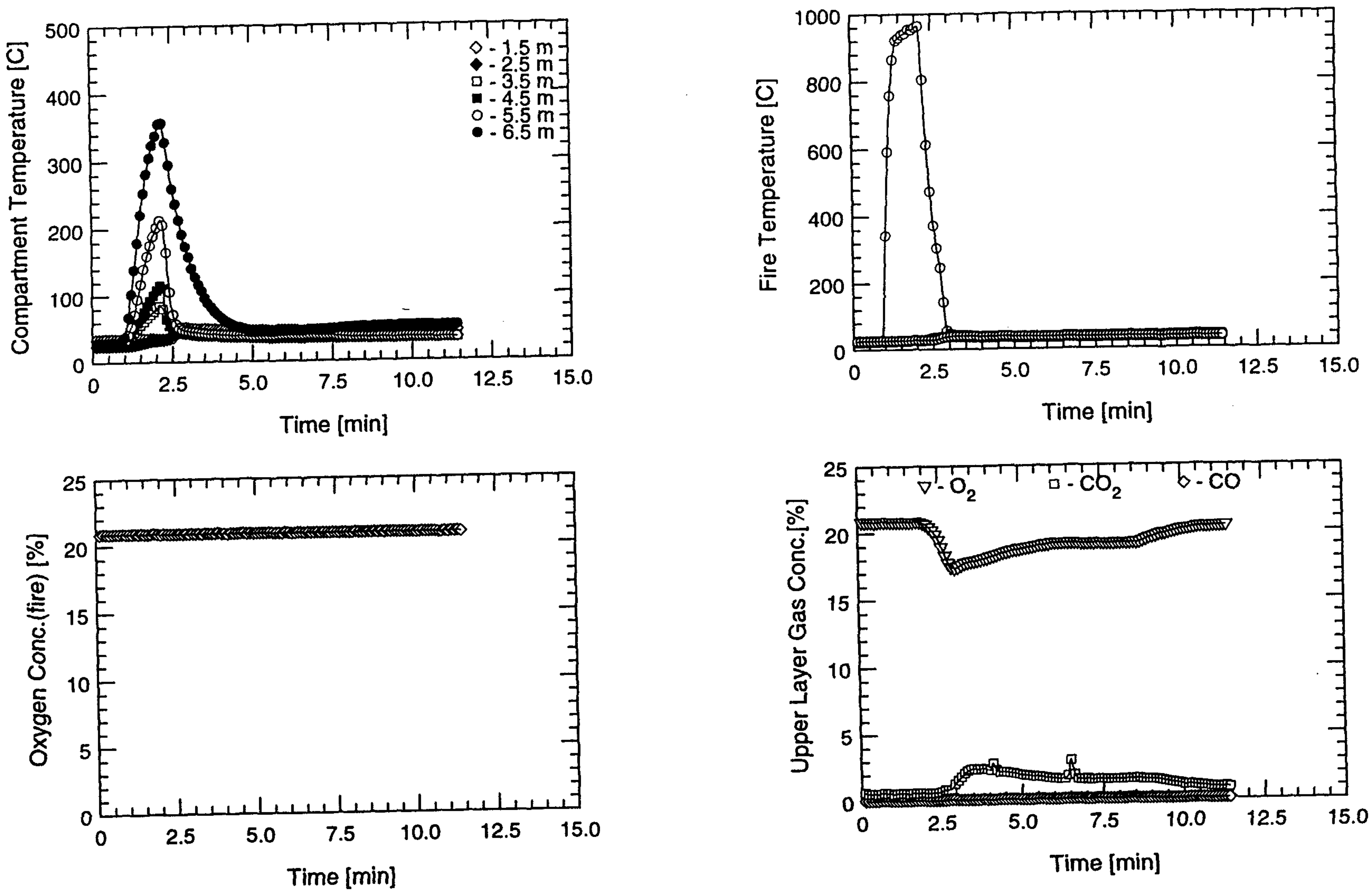

Oxygen Conc.(fire) [%]
Time [min]


Upper Layer Gas Conc.[%]
Time [min]
▽ - O2
□ - CO2
◇ - CO

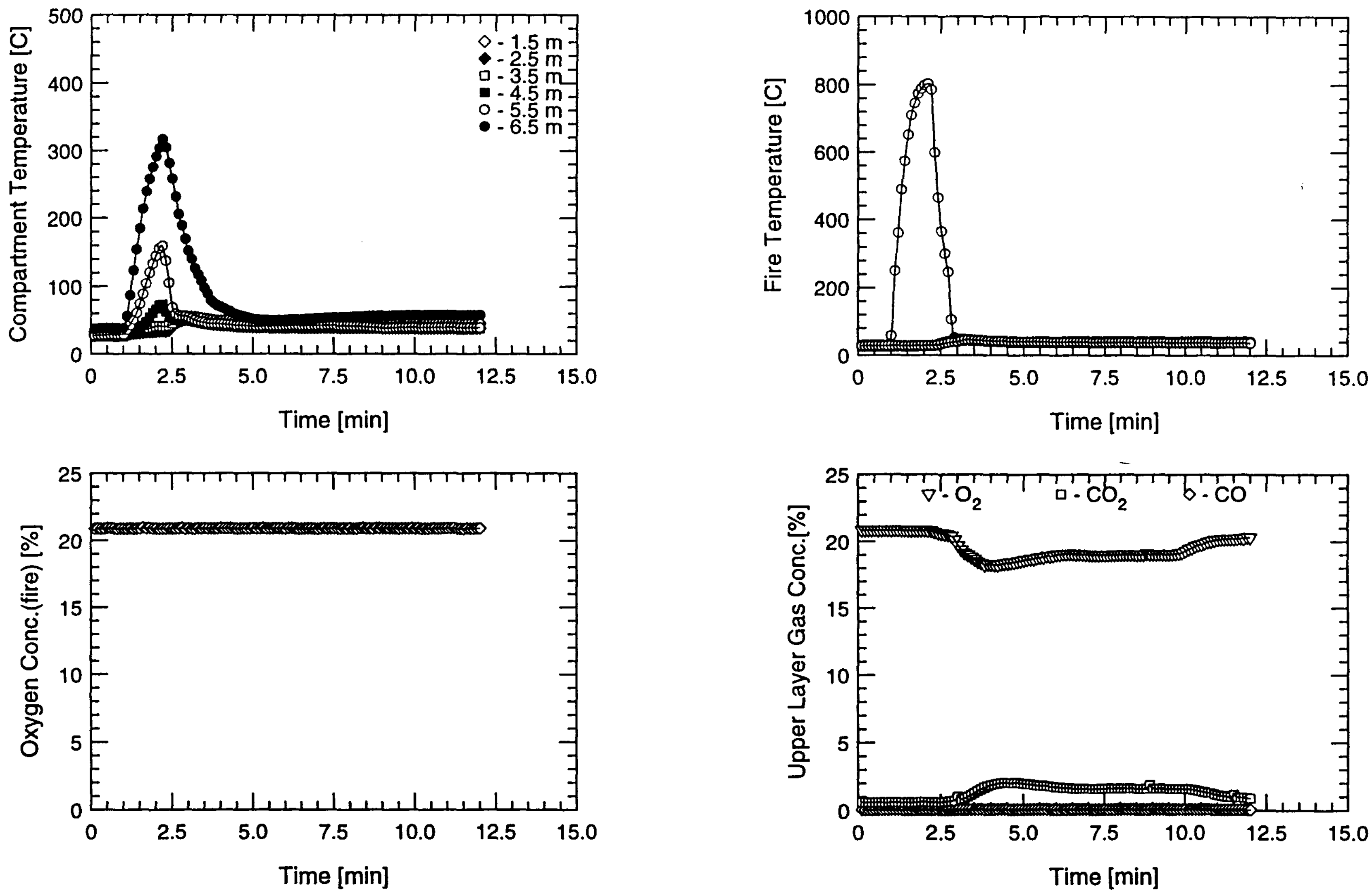
Test #137


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

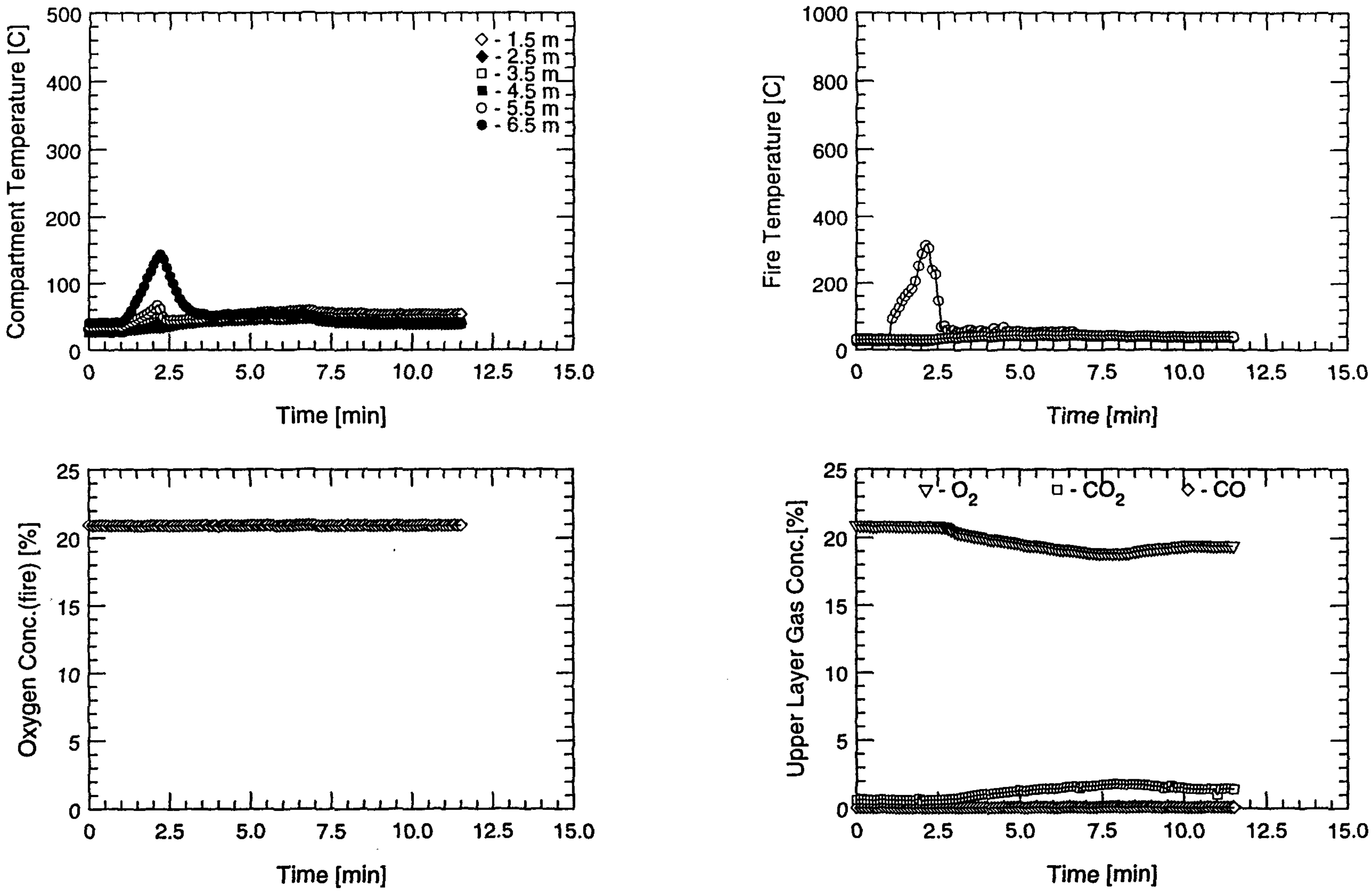
Test #138


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #139

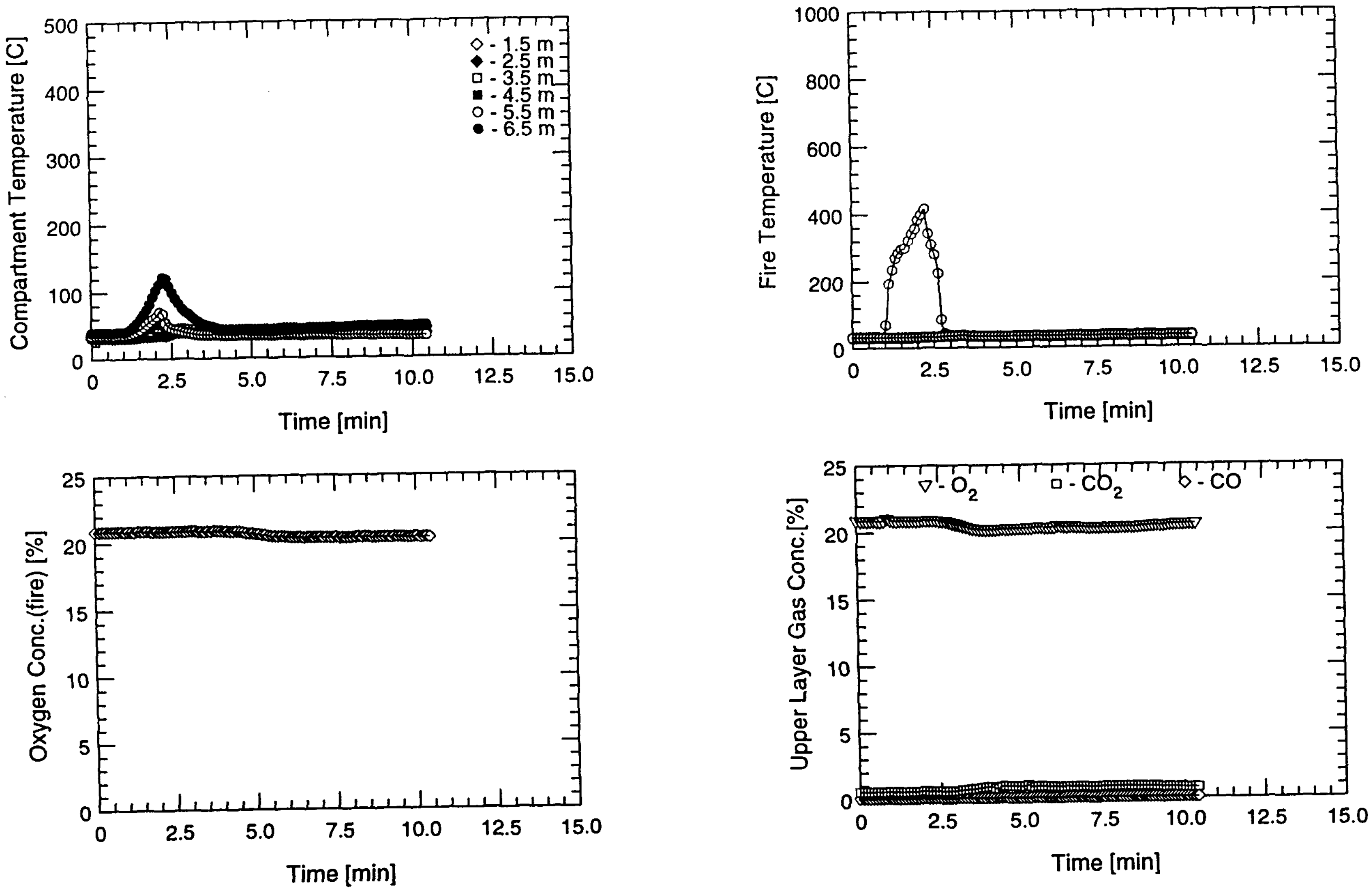

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #140

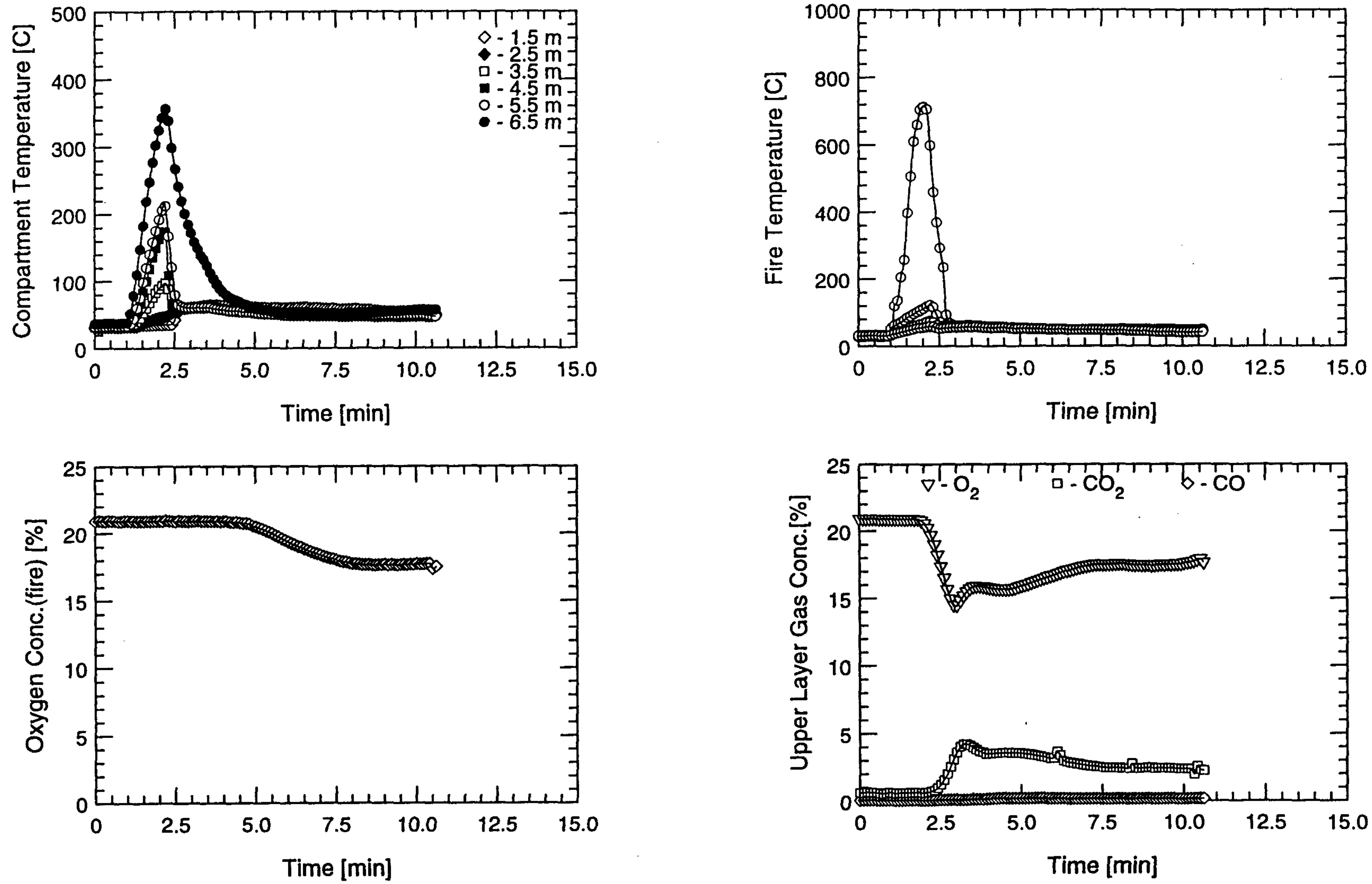


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

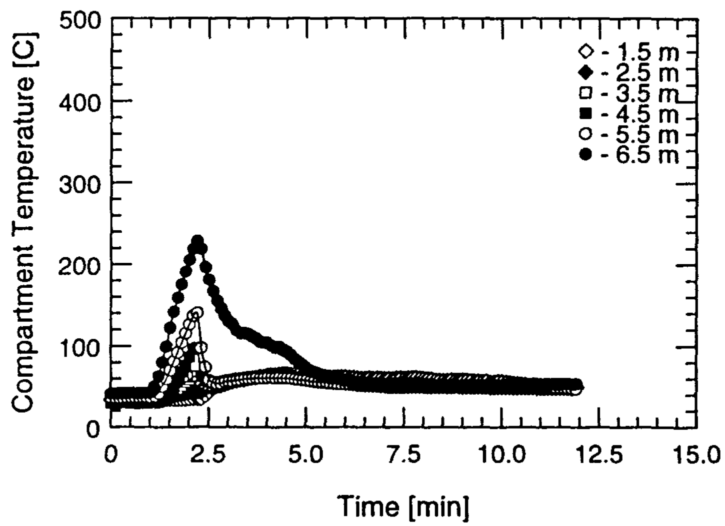
Test #141

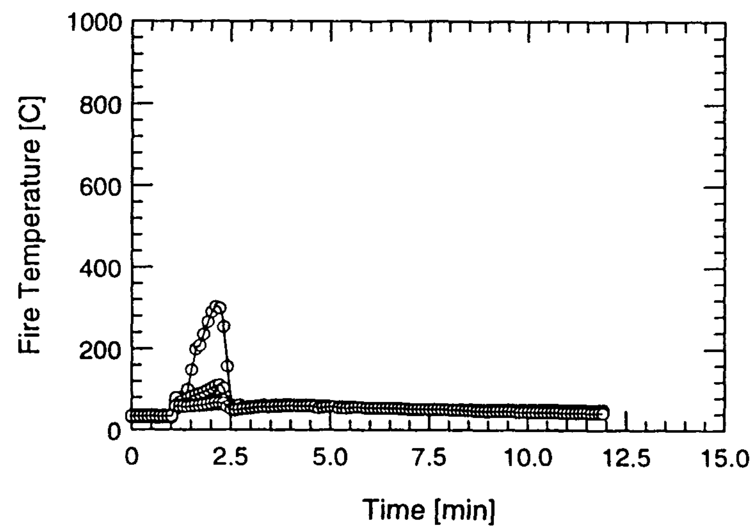

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

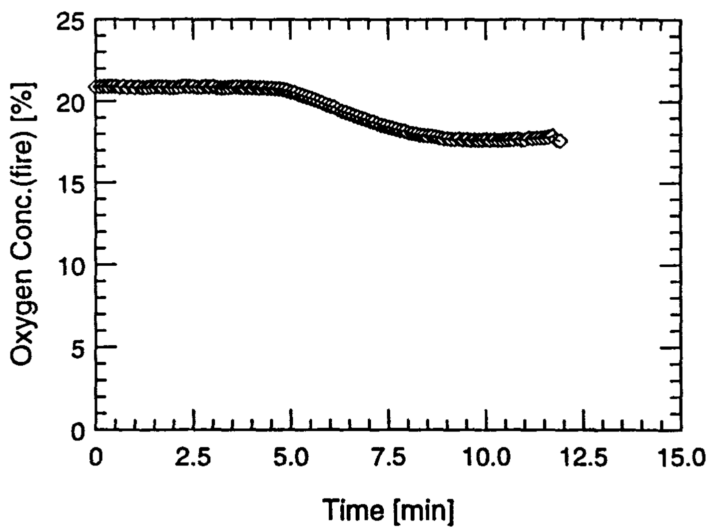
Test #142

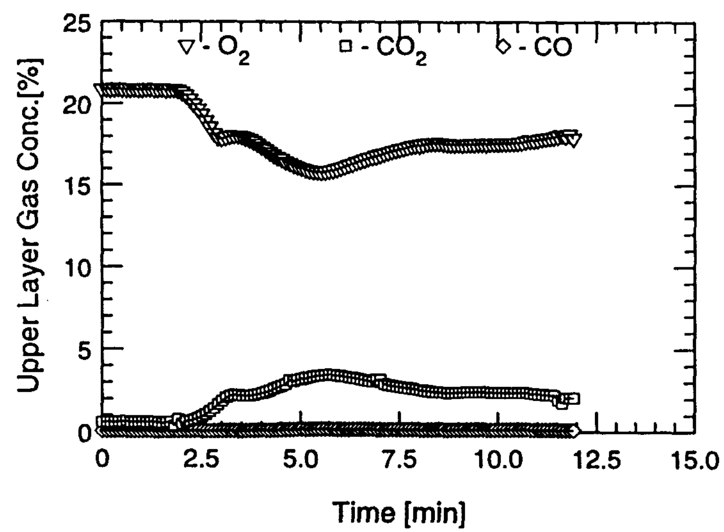

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #143

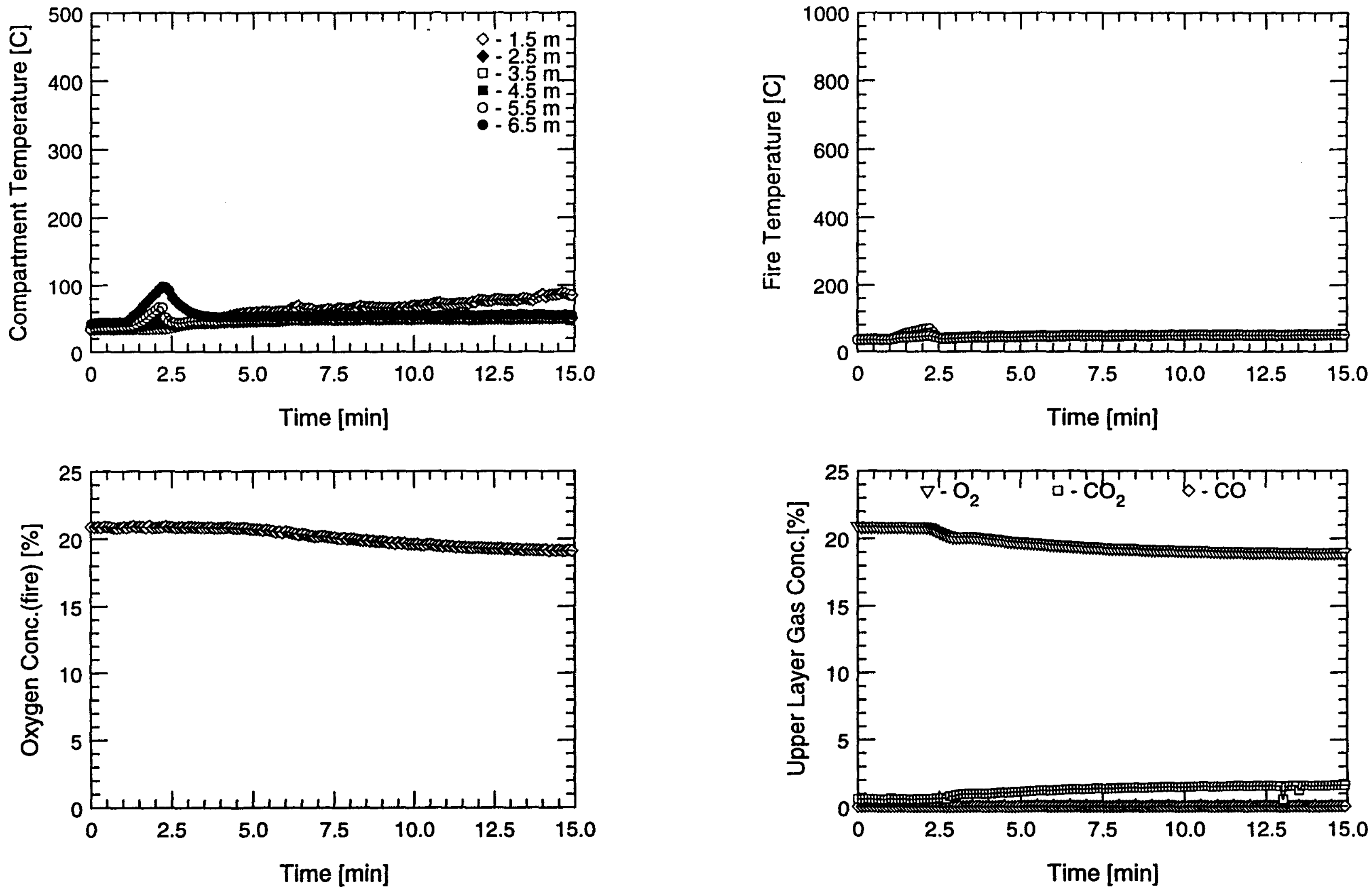

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m


Fire Temperature [C]
Time [min]

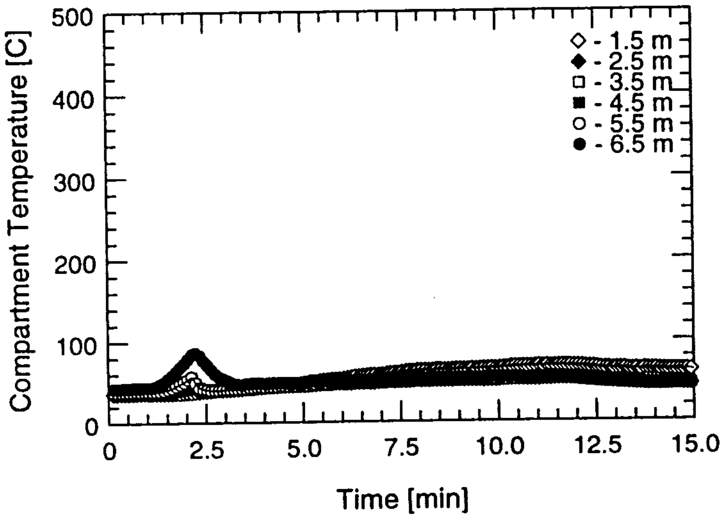

Oxygen Conc.(fire) [%]
Time [min]

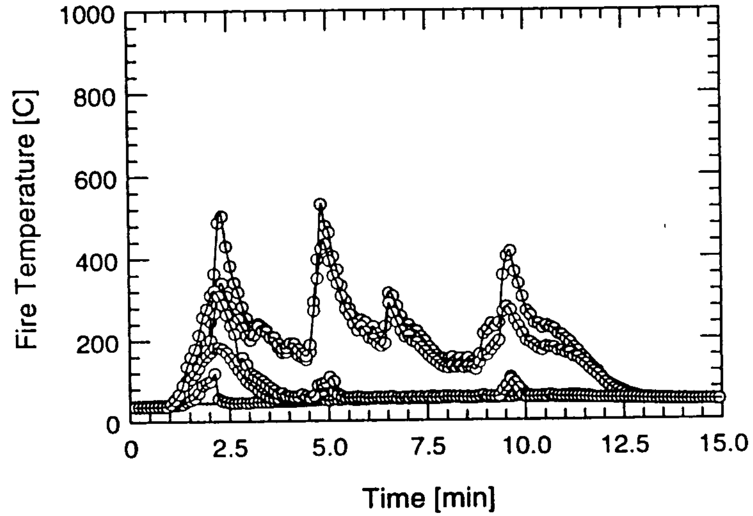

Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

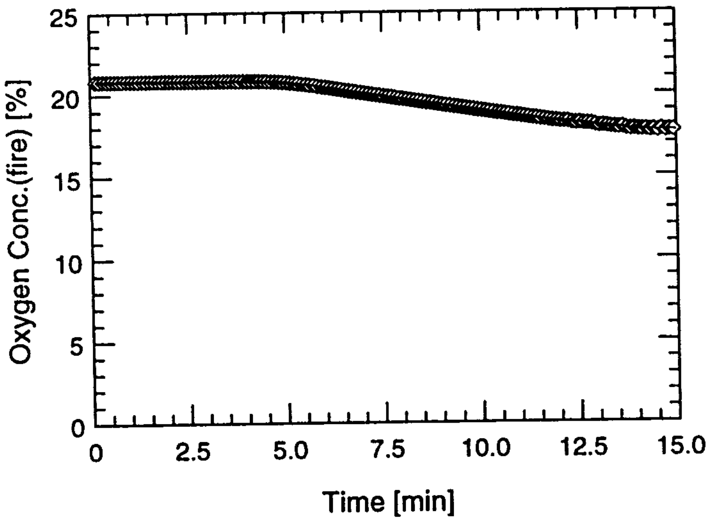
Test #144

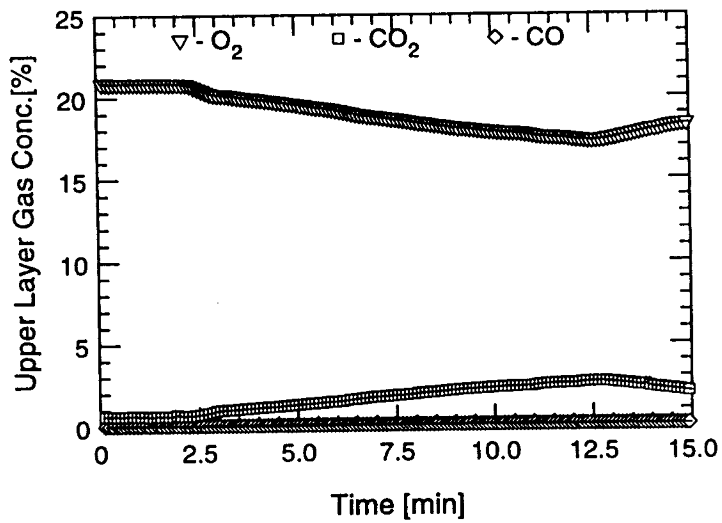

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #145

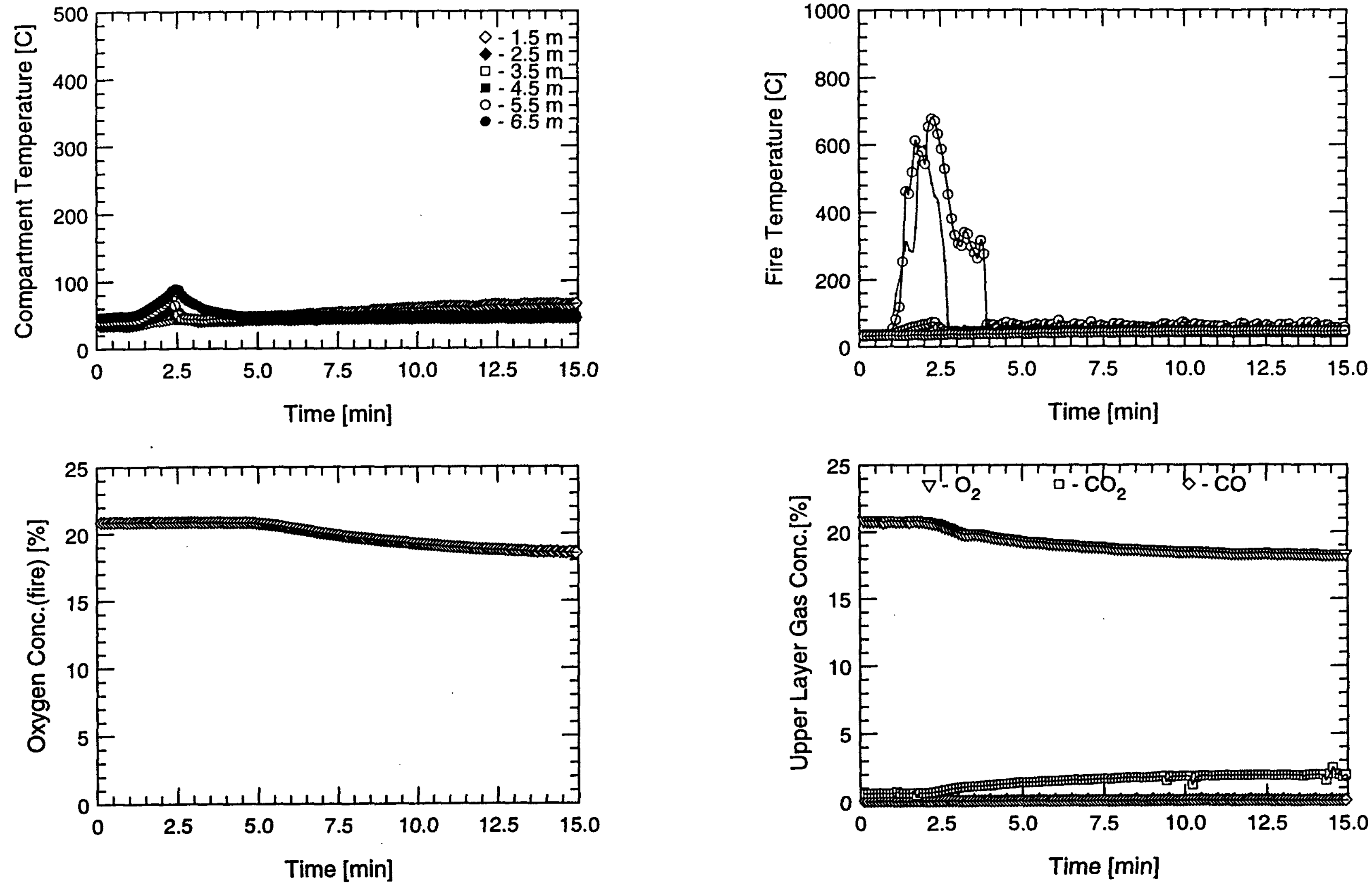

◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Compartment Temperature [C]
Time [min]


Fire Temperature [C]
Time [min]

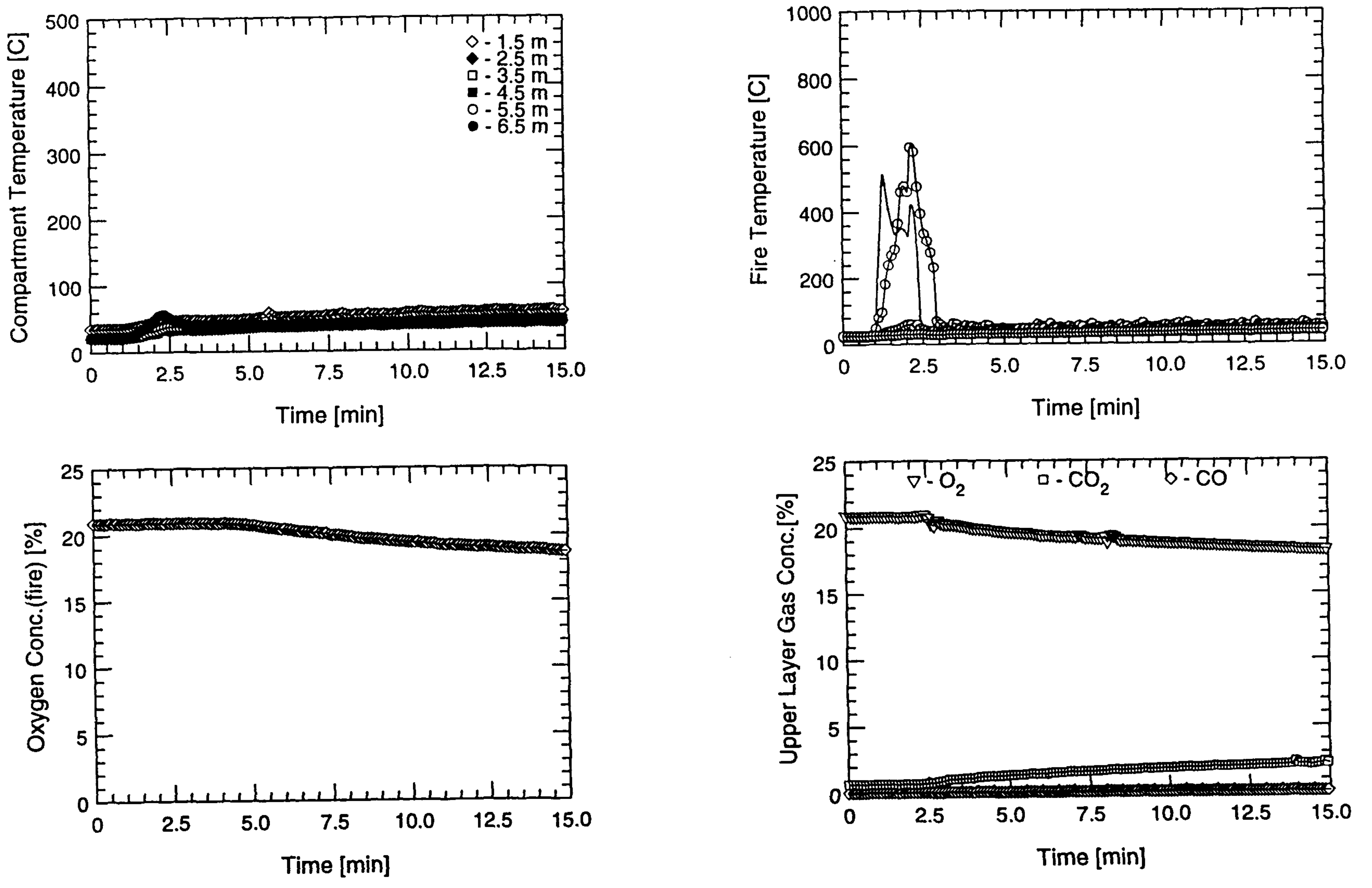

Oxygen Conc.(fire) [%]
Time [min]


▽ - O_2
□ - CO_2
◇ - CO
Upper Layer Gas Conc.[%]
Time [min]

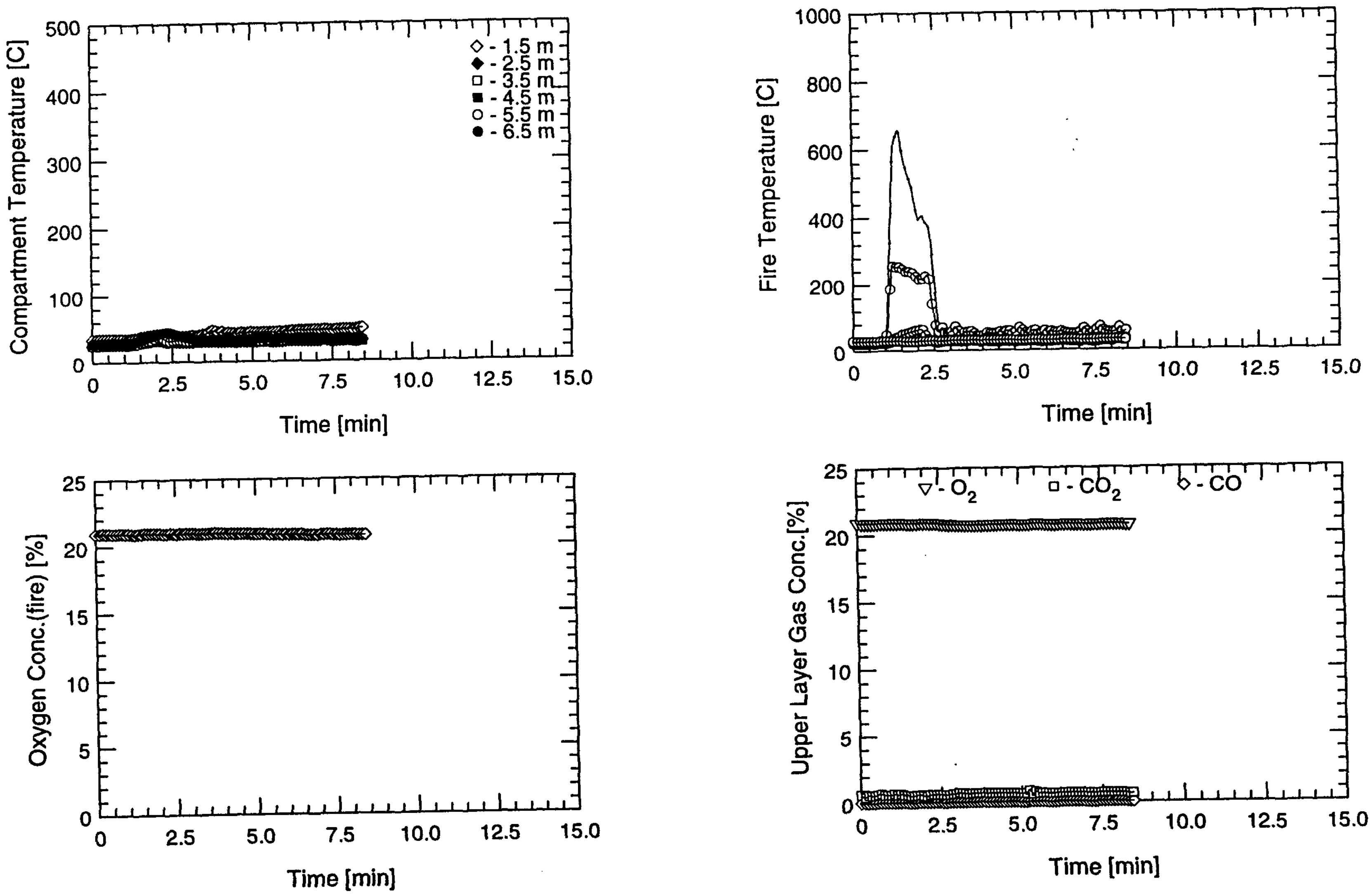
Test #146


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #147

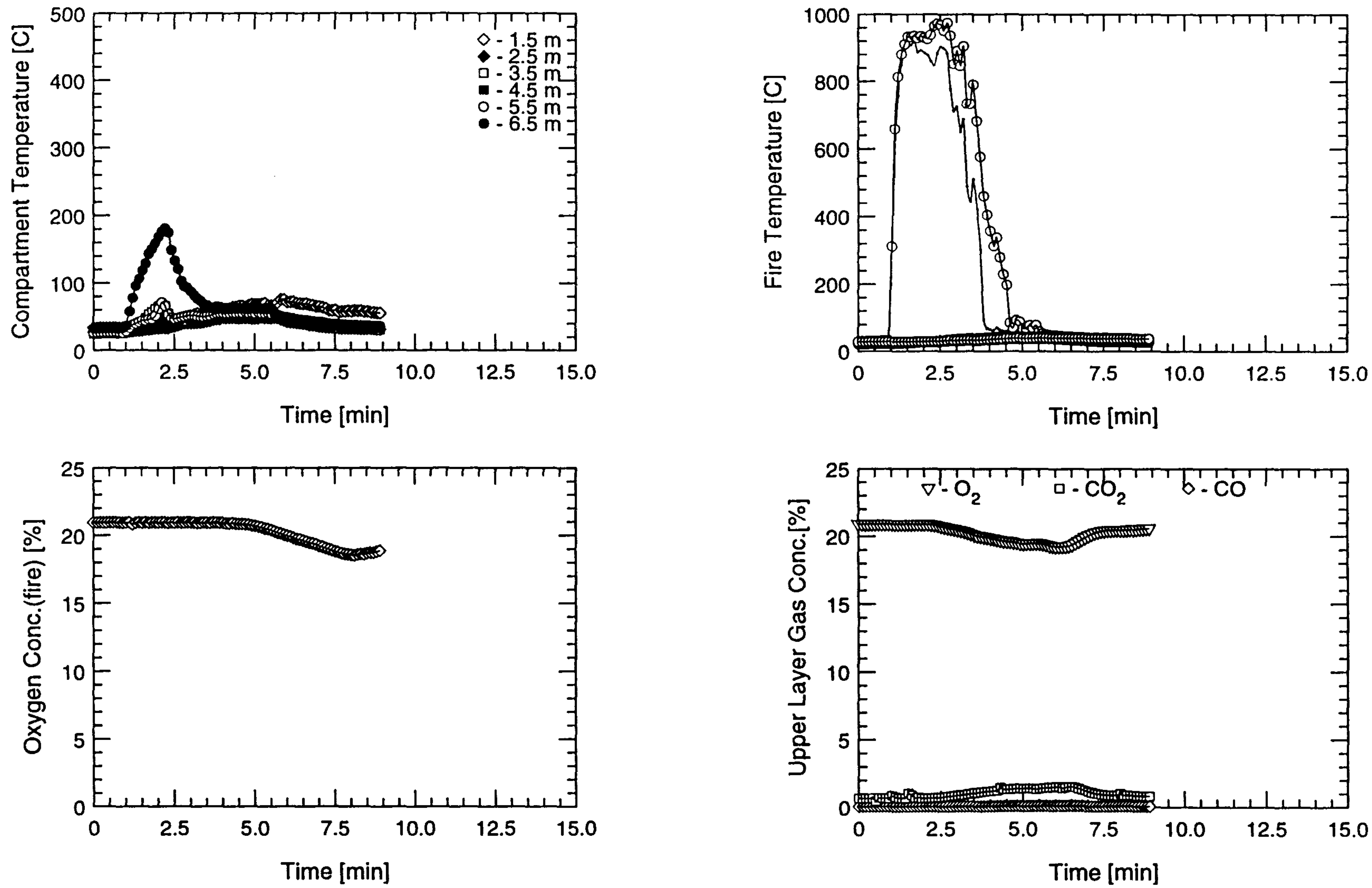

Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #148

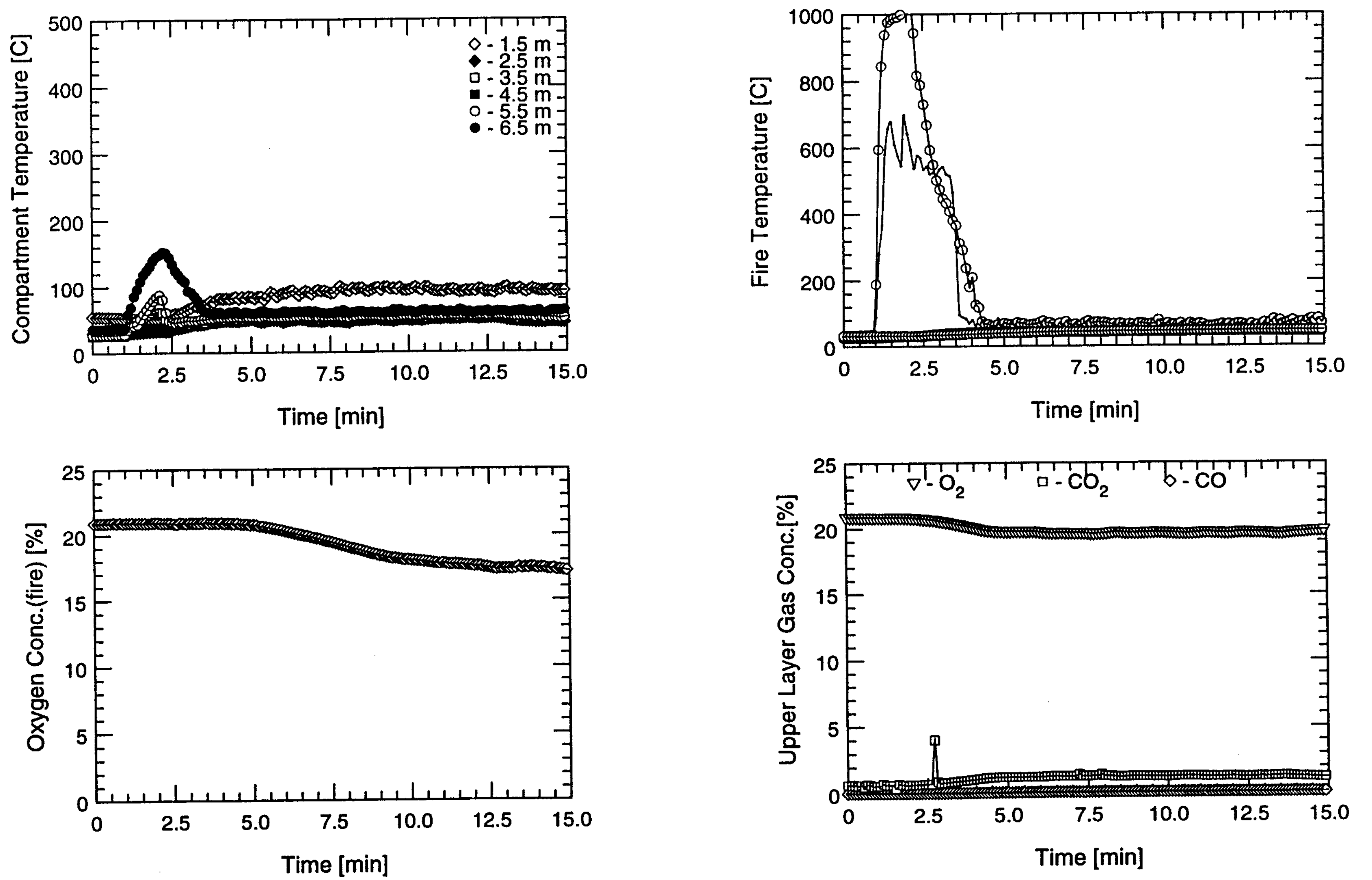


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

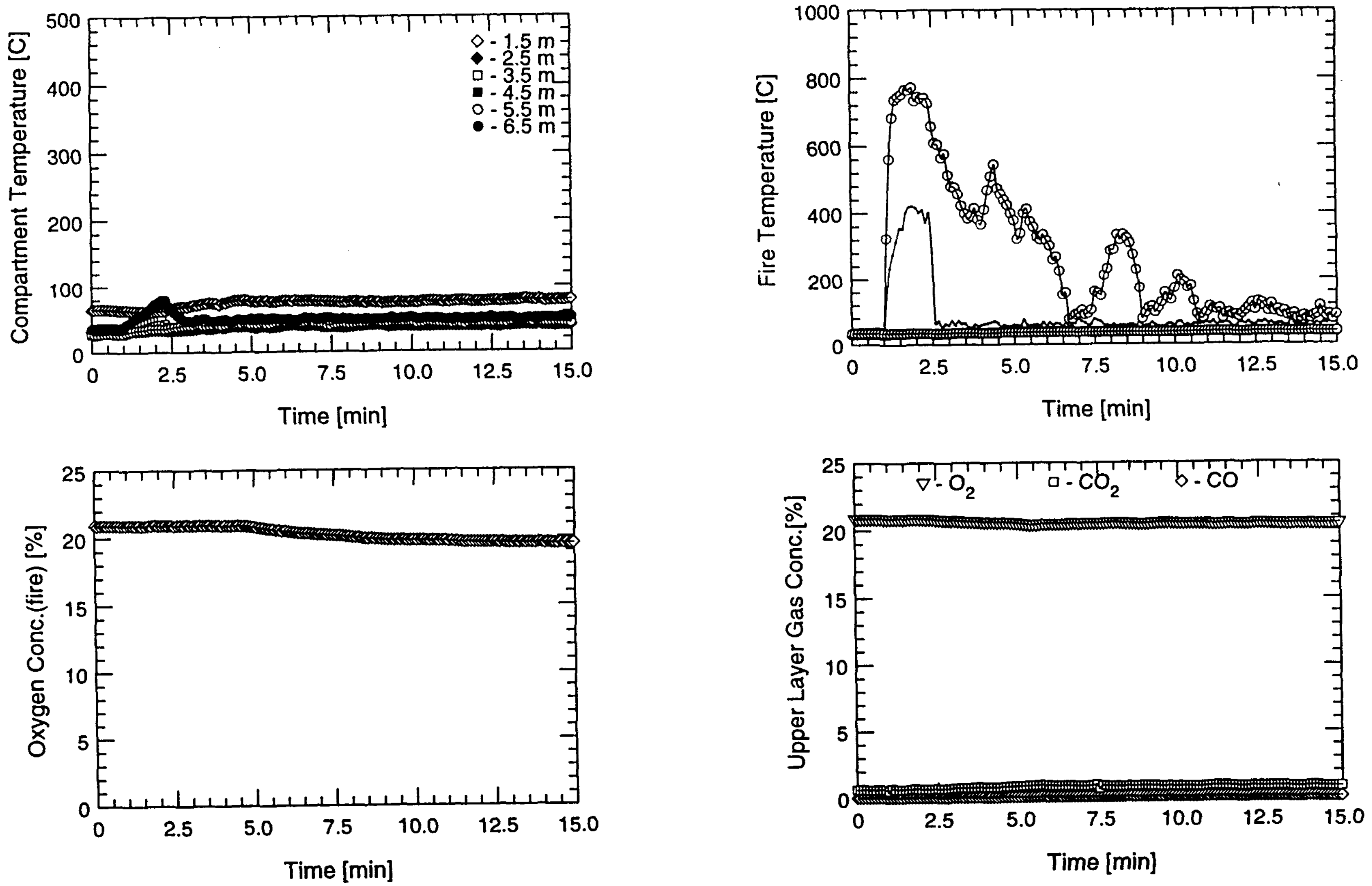
Test #149


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #150

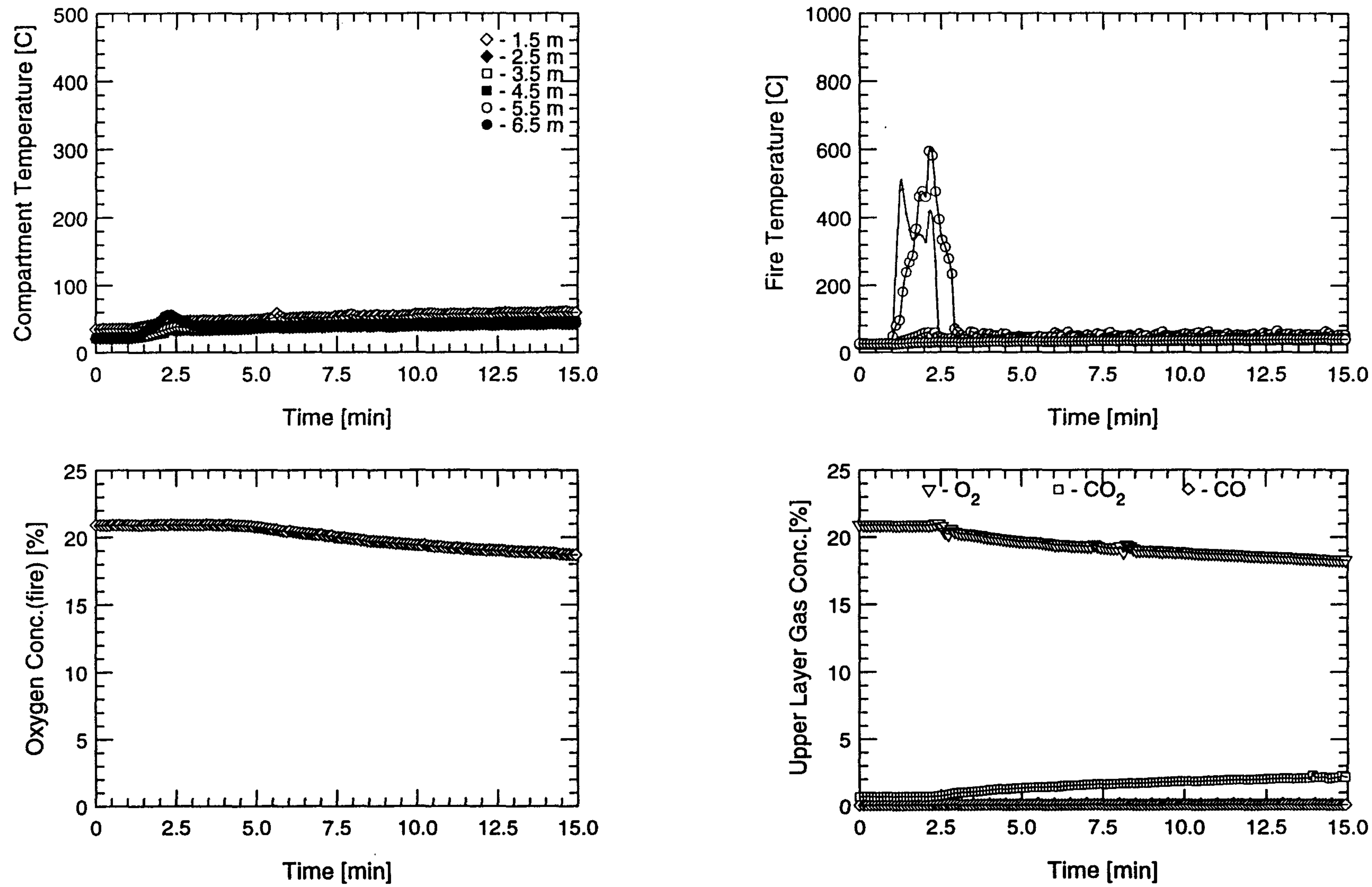

Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #151

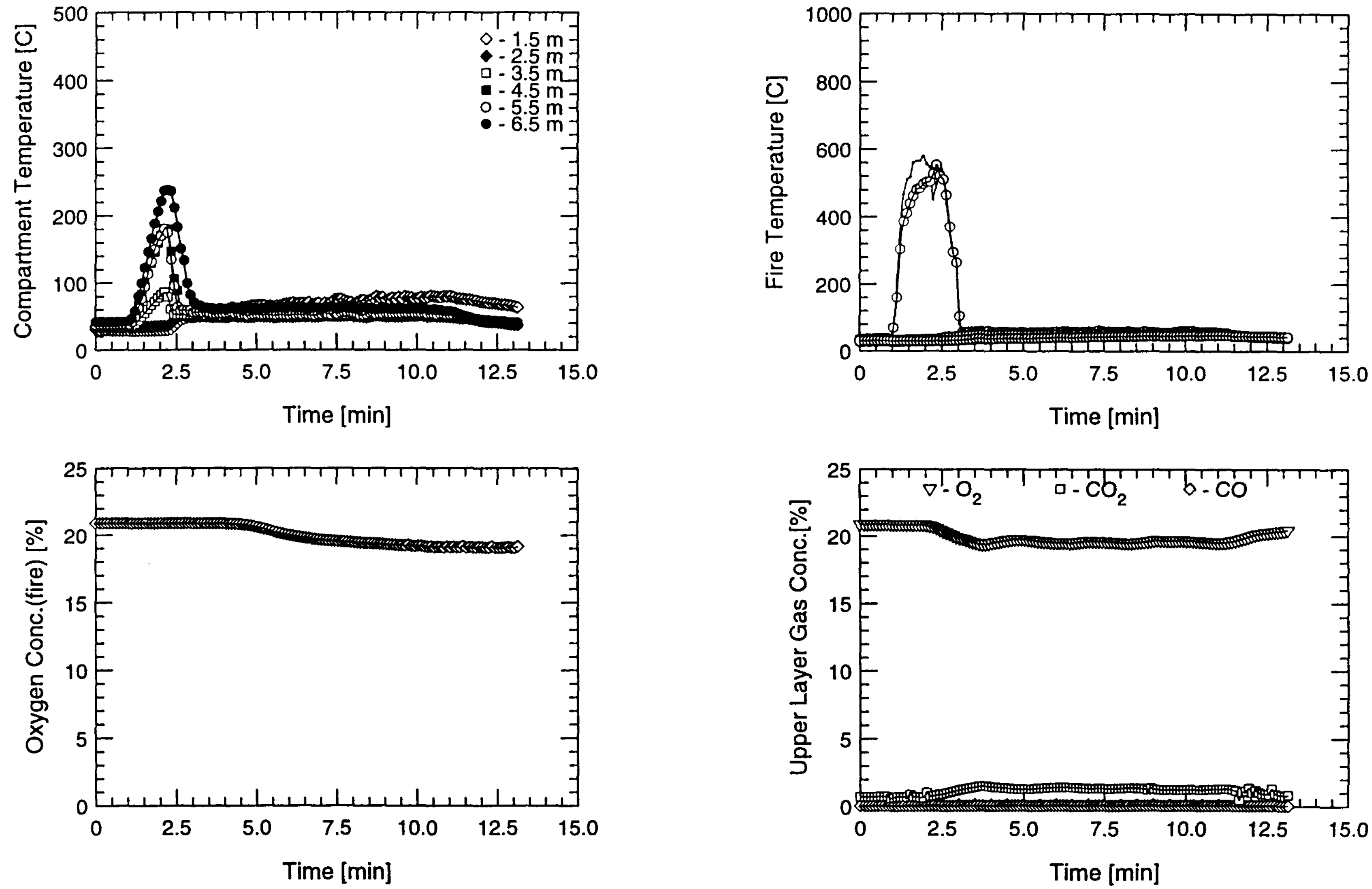


Compartment Temperature [C]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Time [min]
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
▽ - O2
□ - CO2
◇ - CO
Time [min]

Test #152


Compartment Temperature [C]
500
400
300
200
100
0
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
0
2.5
5.0
7.5
10.0
12.5
15.0
Time [min]
Fire Temperature [C]
1000
800
600
400
200
0
Time [min]
Oxygen Conc.(fire) [%]
25
20
15
10
5
0
Time [min]
Upper Layer Gas Conc.[%]
▽ - O_2
□ - CO_2
◇ - CO
Time [min]

Test #153


Compartment Temperature [C]
Time [min]
◇ - 1.5 m
◆ - 2.5 m
□ - 3.5 m
■ - 4.5 m
○ - 5.5 m
● - 6.5 m
Fire Temperature [C]
Time [min]
Oxygen Conc.(fire) [%]
Time [min]
Upper Layer Gas Conc.[%]
Time [min]
▽ - O_2
□ - CO_2
◇ - CO

Test #154

Appendix D

CFAST Input Parameters

CFAST Input File

```
VERSN    2 1 MW Fire in Machinery Space
TIMES    900    60    20    20    0
TAMB   298.  101300.      0.
EAMB   298.  101300.      0.
HI/F     0.00
WIDTH    6.90
DEPTH   11.10
HEIGH    7.30
HVENT   1  2  1   2.000   2.000   0.000   0.000
CVENT   1  2  1   1.00   1.00   1.00   1.00
CEILI STEEL1/2
WALLS STEEL1/2
FLOOR STEEL1/2
CHEMI     0.     0.  12.0    30000000.  300. 400. 0.000
LFBO    1
LFBT    2
FPOS    0.00    0.00    0.00
FTIME    200.    600.    900.
FMASS  0.0000 0.0333 0.0333 0.0000
FHIGH    0.00    0.00    0.00    0.00
FAREA    0.00    0.00    0.00    0.00
FQDOT  0.00      1.00E+06 1.00E+06 0.00
CJET OFF
HCR   0.200 0.200 0.200 0.200
STPMAX  5.00
DUMPR MCS1MW.HI
DEVICE 1
WINDOW  0    0.    0. 1279. 1023. 4095.
```

CFAST Input File

```
VERSN     2 2 MW Fire in Machinery Space
TIMES     900     60     20     20     0
TAMB    298.  101300.       0.
EAMB    298.  101300.       0.
HI/F      0.00
WIDTH     6.90
DEPTH    11.10
HEIGH     7.30
HVENT    1  2  1   2.000   2.000   0.000   0.000
CVENT    1  2  1   1.00   1.00   1.00   1.00
CEILI STEEL1/2
WALLS STEEL1/2
FLOOR STEEL1/2
CHEMI      0.     0.  12.0    30000000.  300. 400. 0.000
LFBO    1
LFBT    2
FPOS     0.00    0.00    0.00
FTIME     200.    600.    900.
FMASS   0.0000 0.0666 0.0666 0.0000
FHIGH     0.00    0.00    0.00    0.00
FAREA     0.00    0.00    0.00    0.00
FQDOT   0.00       2.00E+06 2.00E+06 0.00
CJET OFF
HCR   0.200 0.200 0.200 0.200
STPMAX  5.00
DUMPR MCS2MW.HI

DEVICE 1
WINDOW  0     0.     0. 1279. 1023. 4095.
```

CFAST Input File

```
VERSN    2 6 MW Fire in Mac. Space
TIMES    900    60    20    20     0
TAMB   298.  101300.      0.
EAMB   298.  101300.      0.
HI/F     0.00
WIDTH    6.90
DEPTH   11.10
HEIGH    7.30
HVENT   1  2  1   2.000   2.000   0.000   0.000
CVENT   1  2  1   1.00   1.00   1.00   1.00
CEILI STEEL1/2
WALLS STEEL1/2
FLOOR STEEL1/2
CHEMI     0.     0.  12.0    30000000.  300. 400. 0.000
LFBO   1
LFBT   2
FPOS    0.00   0.00   0.00
FTIME    300.   600.   900.
FMASS  0.0000 0.200 0.200 0.0000
FHIGH    0.00   0.00   0.00   0.00
FAREA    0.00   0.00   0.00   0.00
FQDOT  0.00     6.00E+06 6.00E+06 0.00
CJET OFF
HCR   0.200 0.200 0.200 0.200
STPMAX  5.00
DUMPR MCS6MW.HI

DEVICE 1
WINDOW  0    0.    0. 1279. 1023. 4095.
```